CONSULTANT REPORT

PIER
Public Interest Energy Research
CALIFORNIA ENERGY COMMISSION

Renewable Energy

SOLAR TWO CENTRAL RECEIVER

Gray Davis, *Governor*

STATE OF CALIFORNIA
ENERGY COMMISSION

RESOURCES AGENCY

OCTOBER 1999

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Legal Notice

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million through the Year 2001 to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research.

In 1998, the Commission awarded approximately $17 million to 39 separate transition RD&D projects covering the five PIER subject areas. These projects were selected to preserve the benefits of the most promising ongoing public interest RD&D efforts conducted by investor-owned utilities prior to the onset of electricity restructuring.

What follows is the final report for the Solar Two project, one of five projects conducted by Southern California Edison. This project contributes to the Renewable Energy program.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

Executive Summary

The Solar Two project was funded by the California Energy Commission (the Commission) with Public Interest Energy Research (PIER) transition funds, and was conducted by Southern California Edison (SCE).

The 10 megawatt (MW) Solar One Pilot Plant, which operated from 1982 to 1988 in Barstow, California, was the largest demonstration of first generation power-tower technology. In 1992, a team composed of utilities, private industry, and government agencies retrofitted the 10 MW Solar One Pilot Plant to demonstrate the effectiveness of molten salt power towers. Molten salt power tower technology was pursued because the design decouples the solar collection from the electricity generation better than water or steam systems. In addition, the molten salt power tower approach incorporates a cost-effective energy storage system. This energy storage allows the solar electricity to be dispatched to the utility grid when the power is needed most, increasing the economic value of solar energy.

Converting Solar One to Solar Two required a new molten salt heat transfer system. This included the receiver, thermal storage system, salt piping, and steam generator. A new master control system was also installed.

The Solar Two Test and Evaluation (T&E) activities originally intended were to gather data and information, and perform analyses to:

- Validate the technical characteristics (reliability, annual net electric performance, minimal environmental impact, and capability for dispatch) of the nitrate salt receiver, storage system, and steam generator technologies.
- Improve the accuracy of economic projections for commercial projects by increasing the database of capital, operating, and maintenance costs.
- Simulate the design, construction, and operation of the first 100 MW (or larger) power plants.
- Distribute information to U.S. utilities and the solar industry throughout the world to foster wider interest in the first commercial plants.

The T&E program was originally planned to run for 1 year after final plant acceptance. During this period, the entire plant and operations and maintenance personnel were to be devoted exclusively to T&E with no emphasis on power production goals. This was to be followed by a power production phase lasting approximately 2 years. The start-up and acceptance phases of the project, however, took much longer than expected to complete, because of the following:

- Failure of a receiver tube in June of 1996 that resulted from problems with the installation of the heat tracing on the salt piping system – 5-month outage
- Failure of a tube in the evaporator in November of 1996 – 8-month outage
- Receiver tube leaks discovered in August 1997 caused by stress corrosion cracking – 2-month outage.

These delays and financial considerations forced project management to reevaluate the T&E project structure and seek ways to achieve T&E objectives in a shorter period of time.

Project management and the T&E team determined that all objectives of the T&E project could be met by:

- Setting aside a small period of time (about 1 month) to perform tests requiring the plant in special configuration.
- Then performing the rest of the tests concurrent with routine power production for a period, not less than 1 year, lasting until the end of the project.

Those tests requiring the plant to be in a special configuration were called the "Baseline Test." This term was derived from the fact that most of this testing relates to initial characterization of the receiver and steam generator systems. Although the Baseline Test was scheduled for the month following acceptance testing, much of it was performed in 1997, prior to acceptance.

A major advantage of this new T&E Plan structure, during which all tests essentially run all of the time, is that data was obtained for all four seasons of the year and over a wide range of weather conditions. The new plan also introduced flexibility.

The revised T&E plan included the following tasks:

- Validation of Technical Characteristics (Section 2.0).
- Performance Evaluation (Section 3.0).
- Heliostat Tracking Error (Section 4.0).
- Economic Projection Improvement, ongoing and to be defined in the final T&E material.
- Large Power Plant Simulation, ongoing and to be defined in the final T&E material.
- Information Distribution, ongoing and to be defined in the final T&E material.

This report is intended to outline the T&E portion of the project. The operations and maintenance portion of the project, with the lessons learned, is currently being analyzed and will be ready for publication, with the final T&E material, in roughly 1 year. At that time, the Commission will receive a copy of the final project report, which will include the operations and maintenance report, lessons learned, metallurgical analysis, and other pertinent data.

Validation of Technical Characteristics (Section 2.0)

Objective: Validate the technical characteristics (reliability, annual net electric performance, minimal environmental impact, and capability for dispatch) of the nitrate salt receiver, storage system, and steam generator technologies.

The specific performance goals established for the tests and evaluations were based on predictions from the Solar Two analytical model. SOLERGY, a computer program developed by Sandia National Laboratories to simulate a central receiver power plant, was the code used to model Solar Two.

During the summer of 1998, the plant operated for 32 of 39 days, representing a 94 percent run-day availability after consideration of impacts due to weather and loss of offsite power. Solar Two produced 1,633 megawatthours (MWh) over a 30-day period, exceeding its 1-month performance measure of 1,500 MWh set by the U.S. Department of Energy. The plant also produced a record turbine output of 11.6 MW.

Test No. 3 – Steam Generation System and Electric Power Generation System Characterization (Section 2.1)

Objectives:

- Develop a performance map for the steam generation system (SGS) and the electric power generation system (EPGS).
- Determine the reasons for departures, if any, from the predicted performance values.

Outcomes:

- Steam generator and turbine generator performance as a function of flow rate mapped well with predicted performance.
- The steady-state gross cycle efficiency of the SGS and the EPGS matched the design value of 34 percent.
- The start-up of the SGS and EPGS turbine routinely surpassed the SOLERGY goal, which was that start-up energy usage as low as 6.6 megawatthours thermal (MWht) was achieved.

Recommendation:

- Optimize design and operation of these systems to take advantage of lower start-up energy requirements.

Test No. 6 – Receiver Efficiency Tests (Section 2.2)

Objective:

- Map the receiver efficiency as a function of operating temperature and wind speed.

Outcomes:

- Receiver efficiency, under calm wind conditions, was measured to be 88 percent, which was within 1 percent of the manufacturer's specification.
- The receiver model accurately predicted the receiver efficiency as a function of wind speed within 1 percent.

Recommendation:

- Recommendations for the design of the receiver for the commercial plant will be included in the Final Project Report.

Test No. 8 – Thermal Losses Throughout the Plant (Section 2.3)

Objective:

- Measure the thermal losses of the major Solar Two components (hot and cold salt storage tanks and pump sumps) due to convection, conduction, and radiation.

Outcomes:

- Measured heat loss during steady state conditions was within 8.5 percent of the predicted values.

- Measured heat loss was only 185 kilowatts, which, on an annual basis, corresponds to approximately 1 percent of the total energy supplied to the thermal storage system.

Recommendation:

- Use the information obtained to develop a detailed heat balance for the plant and acquire the data required to design a thermally efficient commercial plant.

Test No. 9 – Parasitic Power Consumption (Section 2.4)

Objective:

- Determine the electric power consumption throughout the plant as a function of operating state.

Outcomes:

- The daily parasitic power consumption for this prototype 10 MW-size plant was initially found to be 23 MWh
- The major problem areas identified were:
  - Heaters left on 24 hours per day throughout the plant.
  - Pumps and other auxiliary equipment were operating longer than needed.
- Optimizing the use of the heaters, pumps, and auxiliary equipment resulted in a 27 percent reduction in parasitic power consumption. Further reduction in the percentage of parasitic power loss is expected as plant size increased.

Recommendation:

- Use the data to minimize parasitic power consumption and assist in the optimization of overall plant performance of the commercial plant.

Test No. 16 – Dispatchability (Section 2.5)

Objective:

- Determine the capability of the plant to dispatch power for different periods of time in differing conditions (throughout the day, through clouds, and in the night).

Outcomes:

- With the molten salt thermal storage system, the plant demonstrated its ability to routinely produce electricity through heavy clouds, after sunset, and throughout the day.
- During one test, the plant produced electricity, around the clock, for 153 consecutive hours (nearly 1 week). This demonstrated the potential to dispatch power independently from the collection of energy from the sun.

Recommendation:

- Use lessons learned to improve design and operation.

Performance Evaluation (Section 3.0)

Objectives:

- Understand and optimize the plant's overall performance.
- Extrapolate Solar Two's performance to general performance of the technology.
- Validate SOLERGY-based predictive tools.

Outcomes:

- It was discovered that, on good solar days when the plant operated all day, plant data agreed well with SOLERGY predictions, and agreed nearly perfectly when a field degradation factor of 10 percent was assumed.
- Tools and procedures to accurate track and evaluate performance were developed.
- The plant never achieved operation at design performance or full production. The reasons for this were:
  - The plant performance is based on its first and only year of operation.
  - Design problems needed to be resolved that contributed to the plants low availability and low power production.
  - The old hardware in the heliostat field was not reliable, reducing heliostat availability and thermal collection.
  - The operations and maintenance personnel were learning plant operations throughout the course of the project and, therefore, operating procedures were not yet optimized.

Recommendations:

- Use SOLERGY to model the performance of power towers that are running in a mature operating state. (Model validation is critical to understanding what contributes to low production and to implement improvements to the plant.)

Heliostat Tracking Error (Section 4.0)

Objectives:

- Explore the geometrical errors that reduce heliostat tracking accuracy.
- Investigate strategies to improve heliostat tracking accuracy at Solar Two.

Outcomes:

- Three significant error sources that adversely affected heliostat tracking accuracy were identified: azimuth tilt, mirror alignment and canting, and encoder references.
- Three strategies were developed to address heliostat tracking errors.
- Although not yet tested on the heliostats, when these strategies were analyzed with the heliostat tracking model, they were found to increase tracking accuracy.

Recommendation:

- Use error-correcting strategies to greatly improve tracking.

Economic Projection Improvement

Objective:

- Improve the accuracy of economic projections for commercial projects by increasing the database of capital, operating, and maintenance costs.

Outcome:

- The operations and maintenance contractor, Edison Services Incorporated (ESI), was required to provide economic data related to the actual operation of Solar Two. This data has not yet been analyzed.

Recommendation:

- A detailed discussion of the economic projections for commercial projects will be included in the Final Project Report.

Large Power Plant Simulation

Objective:

- To simulate the design, construction, and operation of the first 100 MW (or larger) power plants.

Outcome:

- This objective was in progress at the end of the contract period. Evaluation of the design, construction, and operation of Solar Two will continue through the coming fiscal year. Data will be extrapolated as applicable for simulation of the first commercial project.

Recommendation:

- A detailed discussion of the results will be included in the Final Project Report.

Information Distribution

Objective:

- Distribute information to U.S. utilities, and the solar industry throughout the world, to foster wider interest in the first commercial plants.

Outcome:

- Ongoing meeting of this objective will continue through the coming fiscal year.

Recommendation:

- Provide funding to complete the information development and distribution effort.

Summary (Section 5.0)

Main objectives of this Solar Two project were to:

- Demonstrate that the technology worked as predicted.
- Resolve problems that might affect future commercial plants.

The Solar Two pilot plant served that purpose well—identifying the issues and solutions needed to build the next plant successfully. As anticipated in a pilot plant, problems associated with specifics in design, construction, and operation were encountered, including several component failures that resulted in temporary plant outages. None pose a significant threat to the technology. Solutions were found for most issues through design improvements, improved quality control during construction, or modification to operating and maintenance procedures. Most solutions were implemented at Solar Two, but a few are significant enough in scope that they can only be implemented in the next plant. In those cases, workarounds were identified that allowed continued successful operation and testing at Solar Two.

Identifying key issues and their resolution has, in itself, been an important accomplishment of Solar Two. The resulting data will allow performance models to be refined and the performance of future commercial plants predicted with enough confidence to attract investment in the technology.

Key Outcomes include:

- **Efficiency** – The receiver efficiency matched its design specification of 88 percent in low-wind condition and matched modeled results in high winds. The efficiency of the thermal storage system also matched it design goal of >98 percent efficiency. (Outcomes and conclusions for receiver efficiency and thermal storage testing are provided in Sections 2.2 and 2.3 of this report.)
- **Parasitic Power Use** – The electrical parasitic energy load, the electricity required to run the plant, was reduced by 27 percent, demonstrating that the plant routinely met its design goal. (Outcomes and conclusions for parasitic power consumption testing are provided in Section 2.4 of this report.)
- **Dispatchability** – Using its unique and extremely efficient thermal storage system, Solar Two delivered electricity to the grid around the clock for 153 consecutive hours. (Outcomes and conclusions for dispatchability testing are provided in Section 2.5 of this report.)
- **Energy Production** – Solar Two produced 1,633 megawatthours (MWh) over a 30-day period, exceeding its 1-month performance measure of 1,500 MWh set by the U.S. Department of Energy. The plant also produced a record turbine output of 11.6 MW.
- **Reliability** – During the summer of 1998, the plant operated for 32 of 39 days (4 days down because of weather, 1 day because of loss of offsite power, and only 2 days for maintenance), representing a 94 percent run-day availability.

Abstract

Solar Two is a proof-of-concept program intended to provide environmentally sound, zero-emission solar-thermal central receiver electrical generation. The Solar Two program supports the Public Interest Energy Research (PIER) goal of improving the environmental and public health costs and risks of California's electricity by proving zero-emission electrical generation. This portion of the program was intended to complete testing and evaluation of the 10 megawatt (MW) Solar Two plant. This project extended from January 1998 through April 8, 1999, and was conducted by Southern California Edison (SCE) and funded by a consortium of electric utilities, the Electric Power Research Institute (EPRI), three industrial firms, the South Coast Air Quality Management District (SCAQMD), the U.S. Department of Energy (DOE), and the California Energy Commission.

Solar Two consists of a circular field of heliostats to collect and focus the solar radiation on a receiver mounted on a tower standing within the heliostat field. A fluid circulates through the receiver, collecting thermal energy at high temperatures, and flows to an insulated storage tank. Steam for the 10 MW turbine is made as needed by pumping the hot fluid to a heat exchanger. The receiver and energy storage fluid is a commercial molten potassium and sodium nitrate mix used in industrial applications. The Solar Two plant demonstrated the use of molten salt both as a receiver and as an energy storage fluid for the first time in an operating solar-electric generation station.

1.0 Introduction

This report summarizes the activities of the Solar Two Test and Evaluation (T&E) team for the contract period from January 1, 1998 through April 8, 1999. The body of this report describes tests and analyses that received attention during the contract period, and should be viewed as a summary of work in progress and not as a comprehensive description of the testing and evaluation of Solar Two. Analysis and further documentation of the Solar Two data will continue through the remainder of this year. The reports produced during the coming year will contain comprehensive results of all the tests and evaluations conducted during the Solar Two Project. These reports are scheduled for completion in approximately 1 year. As a participant in the Solar Two project, the California Energy Commission will receive a copy of this report when it is published.

As described in the previous report to the Commission, *Final Report Central Receiver Testing and Evaluation, California Energy Commission Contract Number 500-92-027, #2, Dated February 23, 1998*, the protracted start-up period for Solar Two resulted in many changes to the project schedule. The problems associated with the protracted start-up continued to impact both the project schedule and the project funding throughout the contract period. The Solar Two plant was not accepted from Start-up by Operations until February 18, 1998 and operation of the plant ended on April 8, 1999. During this period, the operating and maintenance contractor, Edison Services Incorporated (ESI), had control of the plant. As a result of conservative operating practices implemented by project management, Solar Two was only available for rigorous testing less than 44 percent of that time. This is discussed further in Section 1.4 of this document.

This report begins with a summary of the goals and objectives of the Solar Two Test and Evaluation project, discusses in some depth the evolution of the T&E plan, and provides documentation of the progress made during the contract period.

As a result of the circumstances previously described, Solar Two was available for rigorous testing for a limited time. The test results presented in the following are compared to a number of goals that were established based on the computer code SOLERGY. (SOLERGY is a computer program developed by Sandia National Laboratories used to simulate the operation and power output of a solar central receiver power plant.) These goals were established assuming a mature plant. In the case of Solar Two, this would have been in the third year of operation, that is, after 1 year of T&E, after plant optimization, and after 1 year of power production.

1.1 Program Background and System Description

The 10-megawatt-electric (MWe) Solar One Pilot Plant, which operated from 1982 to 1988 in Barstow, California, was the largest demonstration of first-generation power-tower technology. During operation of Solar One and after its shutdown, significant progress was made in the United States on more advanced second-generation power tower designs. The primary difference between first and second-generation systems is the choice of receiver heat transfer fluid. The Solar One plant used water/steam; the second-generation systems in the U.S. use molten salt.

U.S. solar industry currently prefers molten salt power towers because the design de-couples the solar collection from electricity generation better than water/steam systems and it allows the incorporation of a cost effective energy storage system. Energy storage allows the solar electricity to be dispatched to the utility grid when the power is needed most, which increases the economic value of solar energy. In 1992, a team composed of utilities, private industry, and government agencies joined to demonstrate molten salt power towers at the 10-MWe Solar Two plant, which was constructed by retrofitting Solar One with molten salt technology.

Converting Solar One to Solar Two required a new molten salt heat transfer system (including the receiver, thermal storage, piping, and a steam generator) and a new control system. The Solar One heliostat field, the tower, and the turbine/generator required only minimal modifications. The major Solar Two systems and equipment are described in the following. Figure 1 shows a schematic of the plant.

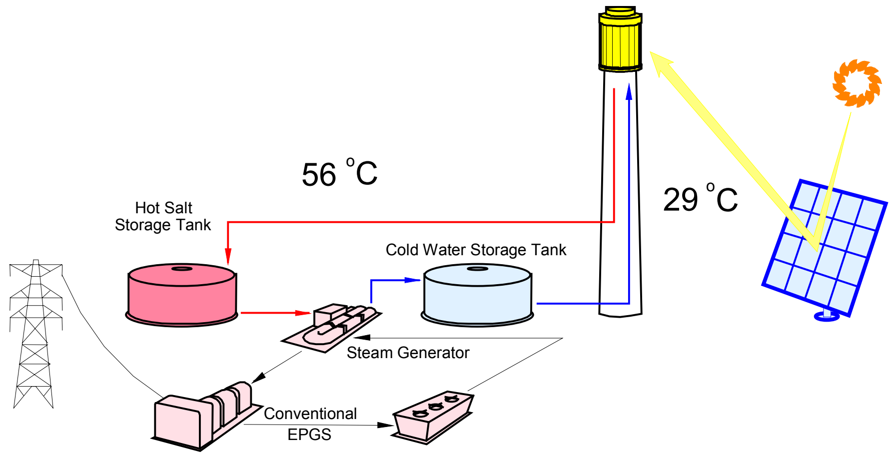

Figure 1. Schematic of a Molten Salt Power Plant

The Bechtel Group, Inc. designed and constructed the new salt system; they developed the plant layout, sized much of the salt handling equipment, and developed specifications for the receiver, storage tanks, steam generation system, and the master control system. The design was based on experience gained from molten-salt receiver and system experiments conducted at the National Solar Thermal Test Facility. Bechtel also installed all of the salt piping (except piping in the receiver system), pumps, sumps, instrumentation and controls. In addition, Bechtel was responsible for plant start-up and acceptance testing.

The Solar Two receiver was designed and built by Boeing North American, Inc. It is rated to absorb 42 MW of thermal energy at an average solar energy flux of 430 kilowatts per meter squared (kW/m^2). The receiver consists of 24 panels that form a cylindrical shell around internal piping, instrumentation and salt holding vessels. Each panel consists of 32 thin walled stainless steel tubes connected on either end by flow distributing manifolds called headers. The external surfaces of the tubes are coated with a black Pyromark® paint that is robust, resistant to high temperatures and thermal cycling, and absorbs 95 percent of the incident sunlight. The receiver is designed to rapidly change temperature without being damaged. For example, during a cloud passage, the receiver can safely change from 1,050 degrees Fahrenheit (°F) to 550 °F in less than 1 minute[1]. The salt fed to the receiver is split into two flow paths. One circuit enters the northernmost west panel and flows west in a serpentine fashion from panel to panel. The other stream enters the northernmost east panel and flows east. After six panels both streams cross over to balance energy collection variations that occur from east to west as a function of the time of day.

The thermal storage tanks were fabricated at the Solar Two site by Pitt-Des Moines. All pipes, valves, and vessels for hot salt were constructed from stainless steel because of its corrosion resistance in molten salt at 1,050 °F. Lower cost carbon steel was used for cold salt containment because of the salt's lower corrosivity at 550 °F. Solar Two was designed with a minimum number of gasketed flanges and most instrument transducers, valves, and fittings are welded in place to minimize salt leaks.

The steam generator system (SGS) was designed by ABB Lummus. It consists of a shell and tube superheater and preheaters and a kettle evaporator. Stainless steel cantilever pumps transport salt from the hot sump through the SGS to the cold tank. Salt in the cold tank flows to the cold sump and is pumped with multistage centrifugal pumps up the tower to the receiver.

The thermal storage medium consists of approximately 3 million pounds of nitrate salt nominally consisting of 60 weight percent (wt%) $NaNO_3$ and 40 wt% KNO_3. The nitrate salt was provided by Chilean Nitrate Corporation of New York. This salt melts at 400 to 428 °F and is thermally stable to approximately 1,115 °F.

The Rankine cycle turbine was refurbished from the Solar One project. It is rated at 12.8 MWe gross generation. It accepts steam from the steam generator at 1450 pounds per square inch gauge (psig) and 950 °F.

The original 1818 Martin Marietta heliostats were also reused from Solar One, but the inner 17 rows of heliostats were refocused for the smaller Solar Two receiver. The area of each of these heliostats is 39.1 meter squared (m^2).

Some of the facets had fallen off in the early 1990's and were replaced with facets from a defunct photovoltaic power plant. Also, 108 large area heliostats were added to the south part of the field to improve the flux profile of the receiver. The area of each of these heliostats is 95 m^2. Figure 2 is a photograph of the Solar Two plant.

Figure 2. Photograph of the Solar Two Plant in Operation

1.2 Goals and Objectives of the Solar Two Test and Evaluation Project

As stated in Bechtel Document 3PS-G-003, rev. 0, *Solar Two Project Test and Evaluation Plan*, (Appendix I of this report) the objectives of the Solar Two T&E project were to gather data, gather information, and perform analyses to:

- Validate the technical characteristics (reliability, annual net electric performance, minimal environmental impact, and capability for dispatch) of the nitrate salt receiver, storage system, and steam generator technologies.
- Improve the accuracy of economic projections for commercial projects by increasing the database of capital, operating, and maintenance costs.
- Distribute information to U.S. utilities and the solar industry to foster wider interest in the first commercial plants.

To meet these objectives, the Solar Two project enlisted Bechtel to develop a T&E Plan, with assistance from the Technical Advisory Committee, which defined:

- The tests and evaluations required to meet the stated project objectives
- The support staffing and equipment requirements to accomplish technology validation
- The schedule and budget for performing the tests and evaluations
- The deliverables resulting from work conducted under the T&E Plan.

Appendix I provides a comprehensive description of the original T&E plans and details of the goals, objectives, and basic procedures for each test and evaluation.

1.3 Revised Solar Two Test and Evaluation Plan

Originally, the T&E project was planned to run for a period of 1 year after final plant acceptance. During this period, the entire plant and operations and maintenance (O&M) personnel were to be devoted exclusively to T&E with no emphasis on power production goals. This was to be followed by a power production phase lasting approximately 2 additional years. The performance goals for the Solar Two Project were not expected to be met until the latter portion of the power production phase. Figure 3 provides the original schedule for these activities, as presented in the T&E Plan.

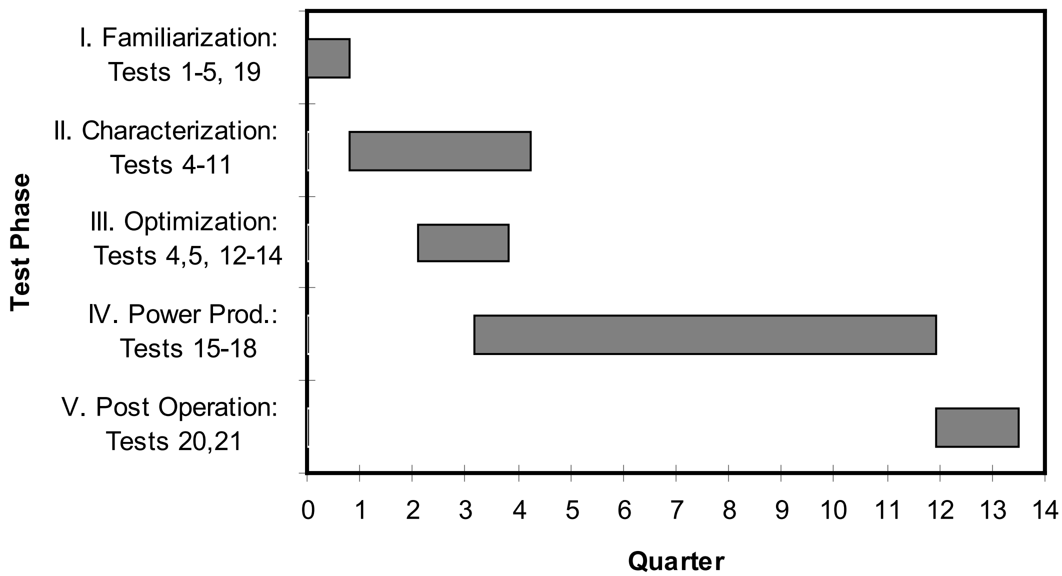

Figure 3. Original Schedule of the T&E Project

Start-up and acceptance phases of the project took much longer than expected, however, largely because of:

- Failure of a receiver tube in June of 1996 that resulted from problems with the installation of the heat tracing on the salt piping system – 5-month outage
- Failure of a tube in the evaporator in November of 1996 – 8-month outage
- Receiver tube leaks discovered in August 1997 caused by stress corrosion cracking – 2-month outage.

These delays and financial considerations forced project management to reevaluate the structure of the T&E project and seek ways to achieve T&E objectives in a shorter period of time. Project management and the T&E team determined that all objectives of the T&E project could be met by:

- Setting aside a small period of time (about 1 month) to perform tests requiring the plant in special configuration.
- Then performing the rest of the tests concurrent with routine power production for a period, not less than 1 year, lasting until the end of the project.

An essential provision in this revised plan was that the acquisition of data must be comprehensive, accurate, and always operational, and that a user-friendly data archive and retrieval system was in place. These conditions ensured that readings from all plant instrumentation were permanently recorded for analyses at a later date. A major advantage of this new structure, where all tests essentially were to run all of the time, was that data were to be obtained for all four seasons of the year and over a wide range of weather conditions. The revised plan also introduced flexibility. In the original scheme, if a certain key instrument was functioning poorly or the weather was wrong for a particular scheduled test, then a delay resulted. Under the revised plan, each test had at least a year to satisfy its critical requirements.

The objectives and operational requirements of each test were evaluated to determine if the test, or parts of the test, required the plant in a special configuration. It was decided that tests that do not require special configurations could be essentially always in progress while the plant is running; i.e., once the project enters its power production/T&E phase. For these tests, data were to be saved and forwarded to the test engineer for analysis. The test engineer was responsible for evaluating the data and reaching conclusions and making recommendations based on the data. The engineer was also responsible for reporting on the test.

Those tests requiring the plant to be in a special configuration were put into a category called the "Baseline Test." This term was derived from the fact that most of this testing relates to the initial characterization of the receiver and steam generator systems. Although the Baseline Test was scheduled for the month following acceptance testing, much of it was performed in 1997, prior to acceptance, for the following reasons:

- The receiver leaks discovered in August of 1997 motivated the Steering Committee to direct the T&E team to perform the receiver efficiency test immediately
- Much of the information related to characterization of the steam generator and electric power generating systems was obtained during the course of acceptance testing.

Consequently, there was no formal Baseline Test period and the project was to enter its Power Production/T&E Phase directly after plant acceptance.

Figure 4 provides a schedule summarizing the revised Solar Two T&E plan.

Figure 4. Revised Schedule of the T&E Project

Table 1 summarizes the tests under the revised T&E Plan and Table 2 summarizes the conditions that must be met to satisfy each test. For periods of time when conditions were satisfied for a given test, the data that were archived were copied and forwarded to the engineer responsible for that test.

Table 1. Tests in the Revised Solar Two T&E Plan

Test No.	Description	Lead Engineer	Revised Test Plan
1	Clear day receiver characterization	Not applicable	Test eliminated except for glint measurements that were added to Test 7. Receiver operation confirmed during acceptance testing. Receiver performance to be documented in Tests 6 and 7.
2	Steam Generator Operation and Electric Power Generation	Not applicable	Test eliminated. SGS/electric power generation system (EPGS) operation confirmed during acceptance testing. SGS heat balance to be added to Test 3.
3	Steam Generation/EPGS Characterization	Jim Pacheco (Sandia)	Test as planned to meet original objectives with addition of confirmation of the heat

Test No.	Description	Lead Engineer	Revised Test Plan
			balance from Test 2.
4	Transient Operation with Simulated Clouds	Greg Kolb (Sandia)	Test as planned to meet original objectives.
5	Heliostat Patterns for Receiver Warm-up	Greg Kolb (Sandia)	Test as planned to meet original objectives.
6	Receiver Efficiency Tests	Jim Pacheco (Sandia)	Test as planned to meet original objectives.
7	Receiver Steady-State Performance	Jim Pacheco (Sandia)	Test as planned to meet original objectives. Includes glint measurements from Test 1.
8	Thermal Losses Throughout the Plant	Jim Pacheco (Sandia)	Test as planned to meet original objectives.
9	Parasitic Power Consumption	Mary Jane Hale (National Renewable Energy Laboratory (NREL))	Test as planned to meet original objectives.
10	Receiver Start-up Following a Heavy Rain	Jim Pacheco (Sandia)	Test as planned to meet original objectives.
11	Receiver Drain During High Wind Conditions	Jim Pacheco (Sandia)	Test as planned to meet original objectives.
12	Optimization of Receiver Loop Operations	Not applicable	To be performed as part of Test 15.
13	Overnight Thermal Conditioning	Greg Kolb (Sandia)	Test as planned to meet original objectives.
14	Optimum Plant Operation	N/A	To be performed as part of Test 15.
15	Power Production	Mary Jane Hale (NREL)	Test as planned to meet original objectives in close coordination with the Performance Evaluation.
16	Dispatchability	Hugh Reilly (Sandia)	Test as planned to meet original objectives.
17	Repeat Key Efficiency and Performance Tests	Not applicable	Efficiency and performance testing will be ongoing as part of the other tests.
18	Coupon Corrosion and Salt Chemistry	Dan Dawson (Sandia)	Test as planned to meet original objectives.
19	Storage Tank Thermal Stresses	Jim Pacheco (Sandia)	Test as planned to meet original objectives.
20	Extended Operational Tests	Not applicable	Not necessary as a stand-alone test. Testing continues as long as the plant operates.
21	Post Test Examinations	Not applicable	This has been eliminated as a T&E procedure. Examinations and evaluations can be defined and performed, if required, based on budget and other conditions at the end of the project.

Table 2. Conditions Needed to Meet Test Operational Criteria

Required Test Conditions	Test No. 1(1)	Test No. 2(2)	Test No. 3	Test No. 4	Test No. 5	Test No. 6	Test No. 7	Test No. 8	Test No. 9	Test No. 10	Test No. 11
Plant Operating Status											
Long-Term Hold								X			
Short-Term Hold			X					X			
Receiver Pre-Heat					X						
Receiver Operating				X		X					
Receiver Operating – Various Power Levels							X				
Receiver Start-up	E	E								X	
Receiver Shutdown and Drain	L	L									X
Normal Power Generation	I	I	X								
Night (Decoupled) Power Generation	M	M	X								
All Modes of Operation	I	I							X		
Weather and Sun Conditions	N	N									
Following a Rain	A	A								X	
Natural Cloud Transients	T	T		X							
Wind Speed 0-10 mph	E	E			X		X	X	X		X
Wind Speed 10-20 mph	D	D			X	X	X	X	X		X
Wind Speed 20-30 mph					X		X	X	X		X
Wind Speed >30 mph					X		X	X	X		X
Wind Speed <5 mph						X					
Clear Sky							X				
Clear Sky – Normal Insolation >400 W/m^2											
Clear Sky – Normal Insolation >800 W/m^2						X					
Clear Sky – Near Sunrise					X						
Clear Sky – Near Solar Noon				X	X	X					
Various											

Notes:

(1) Test deleted except for glint measurements that were moved to Test 7.

(2) Test eliminated. SGS operation confirmed during acceptance testing. Heat balance analysis moved to Test 3.

Table 2. Conditions Needed to Meet Test Operational Criteria (continued)

Required Test Conditions	Test No. 12[3]	Test No. 13[4]	Test No. 14[3]	Test No. 15[5]	Test No. 16	Test No. 17[6]	Test No. 18	Test No. 19	Test No. 20[6]	Test No. 21[7]
Plant Operating Status										
Long-Term Hold										
Short-Term Hold										
Receiver Pre-Heat										
Receiver Operating										
Receiver Operating – Various Power Levels										
Receiver Start-up	E		E			E			E	E
Receiver Shutdown and Drain	L		L			L			L	L
Normal Power Generation	I		I		X	I			I	I
Night (Decoupled) Power Generation	M		M		X	M			M	M
All Modes of Operation	I	X	I	X		I	X	X	I	I
Weather and Sun Conditions	N		N			N			N	N
Following a Rain	A		A			A			A	A
Natural Cloud Transients	T		T			T			T	T
Wind Speed 0-10 mph	E		E			E			E	E
Wind Speed 10-20 mph	D		D			D			D	D
Wind Speed 20-30 mph										
Wind Speed >30 mph										
Wind Speed <5 mph										
Clear Sky										
Clear Sky – Normal Insolation >400 W/m^2										
Clear Sky – Normal Insolation >800 W/m^2										
Clear Sky – Near Sunrise										
Clear Sky – Near Solar Noon										
Various		X		X	X		X	X		

Notes:

(3) Tests 12 and 14 have been eliminated. Optimization studies will be performed as part of Test 15.

(4) The cold salt pump discharge isolation valves have been disabled, precluding testing of the recirculation method for overnight thermal conditioning.

(5) Test 15 to be performed in close coordination with the Performance Evaluation.

(6) Test 17 and 20 were not necessary as stand-alone tests. Testing continued as long as the plant operated.

(7) Eliminated as a T&E activity. Post-project evaluations planned according to budget and other factors at the end of the project.

The T&E Team also reviewed the objectives of the evaluations described in the original T&E Plan and streamlined the organization of this activity. Table 3 lists the evaluations to be performed under the revised T&E Plan. Although the organization and schedule of the original T&E Plan were changed, its objectives, tests, and deliverables remained essentially as initially described. A final activity for the T&E Team would be to apply information gained during the tests and the evaluations to the design, economic analysis and performance prediction for a hypothetical commercial plant.

Table 3 summarizes the schedule for this task and the evaluation activities.

Table 3. Evaluations in the Revised Solar Two T&E Plan

Evaluation	Lead Engineer	Description
Performance Evaluation	Mary Jane Hale (NREL)	The objective of Solar Two's performance evaluation and prediction activity is to determine and understand the plant's performance (on a daily and annual basis). This activity was scheduled to identify potential improvements to plant operating procedures, extrapolate Solar Two's performance to general performance of molten salt central receiver technology, and recommend revisions to predictive models and engineering design methods for Solar Two and future-generation molten salt central receiver technology.
Availability/ Maintainability	Greg Kolb (Sandia)	The objectives were to track availability of major plant equipment and analyze equipment maintainability. Use the forced outage rate for Solar Two to characterize mean time between failures and to identify important equipment vulnerabilities. Use these measurements and the upgrades identified to predict a forced outage rate for a commercial plant.
Operability and Controllability	Greg Kolb (Sandia)	The objective was to characterize the operability and controllability of Solar Two and apply this information to a commercial plant.
Equipment Lifetime	Jim Pacheco (Sandia)	The objective was to assess the equipment life expended during the T&E project; document the actual thermal transients that components experience and compare to procurement specifications; make recommendations to reduce damaging conditions in the plant; and extrapolate results to the commercial plant design.

1.4 Actual Power Production/T&E Phase

The Solar Two Plant was accepted from Start-up by Operations on February 18, 1998 and operation of the plant continued through April 8, 1999. Figure 5 provides a summary of the activities during the Power Production/T&E Phase of the Solar Two Project. A brief discussion of these activities is provided in the following.

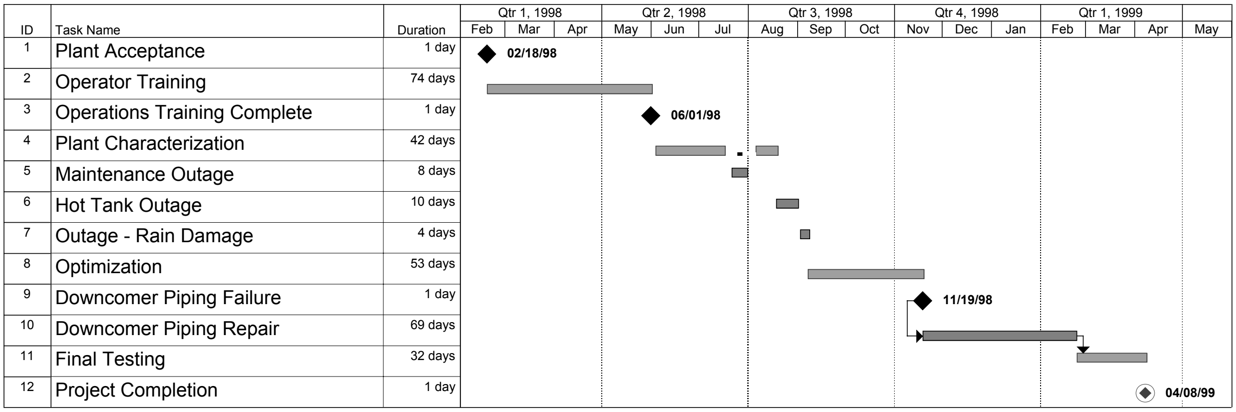

Figure 5. Solar Two Power Production/T&E Phase Actual Schedule

After plant acceptance on February 18, 1998, a period of operator training began. The operator training was completed June 1, 1998. During this period, plant operation was allowed only under the oversight of a Bechtel technician. An extremely conservative approach to operating the Solar Two systems was adopted during this period.

Plant characterization began on June 4, 1998. This was a period of familiarization for the operators and a chance for the T&E Team to study the characteristics of the as-built Solar Two Plant. Operations used this time to develop the confidence and procedures necessary to operate Solar Two near to design levels.

During the summer of 1998, the plant operated for 32 of 39 days (4 days down because of weather, 1 day because of loss of offsite power, and only 2 days for maintenance), representing a 94 percent run-day availability. Solar Two produced 1,633 megawatthours (MWh) over a 30-day period, exceeding its 1-month performance measure of 1,500 MWh set by the U.S. Department of Energy. The plant also produced a record turbine output of 11.6 MW.

Plant characterization was interrupted on August 19, 1998 when a maintenance technician reported an anomaly on the hot salt storage tank. The technician was working on the insulation for the hot tank. He stated that the tank rapidly expanded creating a bulge at the girth of the tank, then snapped back in shape. The tank was drained and a series of inspections undertaken. These included visual inspections of the tank (internal and external) and ultrasonic testing of the tank wall. No defects were detected. The plant restart commenced on September 1, 1998. Prior to completing the restart, a severe rainstorm resulted in substantial damage to the receiver electrical heat trace circuits. The conduit had not been properly sealed during construction and water accumulated in live electrical junction boxes. This delayed the plant restart. The plant was returned to service on September 8, 1998, and no further hot tank problems were observed.

The Plant Optimization Phase was entered after the September 8 restart. Solar Two produced 1,633 MWh over a 30-day period, exceeding its 1-month performance measure of 1,500 MWh set by the U.S. Department of Energy. The plant also produced a record turbine output of 11.6 MW.

In early November, Project Management reviewed the financial status of Solar Two and determined the remaining project funding would only sustain operation until the end of 1998. It had been previously assumed that the Department of Energy fiscal year 1999 funding would sustain operation until approximately the middle of calendar year 1999. To attempt to extend the life of the project, plant operation and maintenance activities were cut back to 5 days a week with operation and maintenance on day shift only.

On November 16, 1998, a through-wall failure of the downcomer piping resulted in a plant shut down. A similar failure had occurred during the Start-up Phase and had been attributed to a construction problem. A detailed review of the stress calculations for the downcomer piping determined that a design error was the cause. An agreement to repair the downcomer and operate Solar Two for a short period of time was reached between the Department of Energy and the O&M contractor. The objective was to complete a limited number of critical tests prior to the final shutdown of the project. The plant was restarted on February 23, 1999. Receiver testing continued until April 8, 1999.

A detailed discussion of the testing and events that occurred during the Solar Two project will be included in the Final Project Report.

2.0 Testing Accomplished During the Contract Period

This section presents the results of testing and analysis completed during the contract period January 1, 1998, through April 8, 1999. Analysis of the test data obtained during this period is continuing. The results of these analyses will be presented in the Final Project Report. As a participant in the Solar Two Project, the California Energy Commission will receive a copy of this report when it is published.

2.1 Steam / Electric Power Generation Systems Characterization – Test 3

2.1.1 Objectives

The objectives of the steam generator system (SGS)/electric power generation system (EPGS) Characterization Test were to develop a performance map for the steam generator and the turbine/generator systems and determine the reasons, if any, for any departures from the predicted performance values.

2.1.2 Method

Table 4 describes the test intended to measure the SGS and EPGS performance over a range of power loads and two inlet salt temperatures. All the subtests, except the first, deviated from normal plant operation. Testing was performed under steady-state conditions where the unit was held at that state for a minimum of 2 hours, but typically 3 to 8 hours. Additionally, the steam generator and turbine/generator start-up and overnight hold operating modes were to be characterized so the energy usage in these states could ultimately be optimized.

Table 4. Desired and Actual Steady State Operating Load Conditions

Test No.	Hot Salt Temperature °F (Desired/Actual)	Salt Outlet Flow % Full Flow	Salt Outlet Flow lbm x 10^{-3}/hr (Desired/Actual)	Pressure (psia)	Steam Temperature °F (Desired/Actual)	Actual Gross Electrical Output (kW-electric)
1	1,050/1,010	100	655/686	1,465	1,000/990	10,570
2	1,050/1,010	80	524/554	1,465	1,000/993	8,880
3	1,050/1,008	60	393/435	1,465	1,000/997	5,900
4	1,050/960	40	262/143	1,465	1,000/955	1,310
5	1,065/1,035	100	655/655	1,465	1,015/1,008	10,930
6	1,065/1,028	80	524/548	1,465	1,015/1,008	9,170
7	1,065/1,024	60	393/371	1,465	1,015/1,009	5,830
8	1,065/978	40	262/143	1,465	1,015/972	1,300

For the steady state operations test, the steam generator system and the electric power generation system were operated together to measure the gross thermal conversion efficiency at the various loading conditions.

The desired steam generator salt inlet temperature of 1,050 degrees Fahrenheit (°F) was not achieved. Although the receiver outlet temperature set point was 1,050 °F in the first four tests and 1,065 °F in the last four tests, the salt entering the steam generator was typically about 38 °F cooler due to attemperation from leaky valves and thermal losses. Also, at low salt flow rates, the operating procedure dictated that the cold mixer pump be in operation. This further decreased the inlet salt temperature by approximately 48 °F. The project purchased new gate valves to eliminate the valve problem, but they were not installed due to financial constraints.

The energy required to start the SGS/EPGS was measured on a daily basis and compared to the assumptions used by the SOLERGY computer code. SOLERGY, a computer program used to simulate the operation and power output of a solar central receiver power plant, was the code used to model Solar Two performance.

2.1.3 Results

Figure 6 plots the measured gross turbine electrical output as a function of the heat input to the steam generator. The heat balance values calculated by Bechtel during the design phase of the project are also shown. The measurements agree well with design estimates. Figure 7 plots the gross cycle efficiency (gross electrical power output divided by thermal power input to the steam generator system) against salt flow rate. Also shown is the design calculated gross cycle efficiency. Again, the measurements agree well with the design calculations. The inlet salt temperature has only a slight effect on both the efficiency and gross power output.

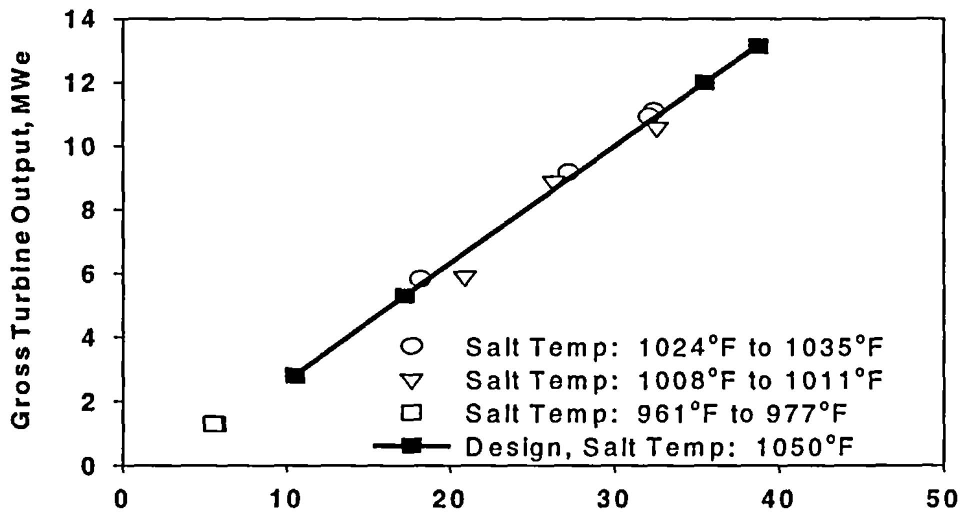

Figure 6. Gross Turbine Electrical Output as a Function of Heat Input to the Steam Generator

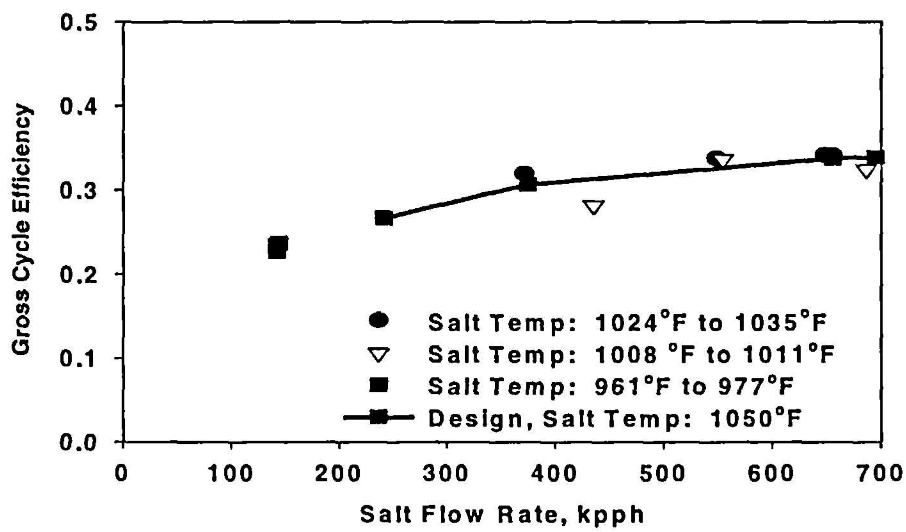

Figure 7. Gross Cycle Efficiency as a Function of Salt Flow Rate

The heat exchanger effectiveness for the pre-heater, evaporator, and superheater were calculated. The effectiveness is defined as the ratio of the actual heat transferred to the maximum possible heat transfer based on actual flows and inlet and outlet temperatures of the salt and water. Table 5 shows the results. It is apparent from this data that the pre-heater effectiveness was low. In August of 1998, after these tests, the flange on the pre-heater was removed and the tubes were found to have fouling and plugging. The inspection also found that the partition plate gasket was eroded away. This allowed feedwater flow to bypass the tube portion of the exchanger and contributed significantly to the reduced effectiveness. It was determined that the original gasket supplied by the heat exchanger manufacturer was inappropriate for the design water temperature and pressure. The gasket was replaced with a high temperature and pressure gasket.

Table 5. Steam Generator Heat Exchanger Effectiveness

Salt Flow (kpph)	Salt Temp °F	Pre-Heater Effectiveness	Evaporator Effectiveness	Superheater Effectiveness
373	1,024	0.42	0.75	0.98
437	1,008	0.45	0.75	0.98
548	1,027	0.47	0.74	0.96
556	1,011	0.48	0.74	0.97
651	1,035	0.46	0.73	0.96
659	1,035	0.40	0.74	0.95
691	1,011	0.47	0.74	0.96

After replacement of the gasket and cleaning, the performance improved dramatically, yielding a record gross turbine output of 11.6 megawatt-electric (MWe).

The steam generator was also evaluated from a total operational system perspective. Actual operating data was compared to predictions from a Solar Two model. To gain a more detailed understanding of how the performance of the steam generator compares with the SOLERGY goals, the "input-output" plot shown in Figure 8 was used. Each point on the plot is the performance of the plant on a particular day and the line is the SOLERGY goal. By studying the plot it can be seen that plant optimizations resulted in frequently meeting the energy conversion goal during October and November. There are two reasons why the energy conversion goal, depicted in Figure 8, was being met routinely. First, the operators were running the turbine at full output power much more frequently. Operating the turbine in this way is more thermodynamically efficient than running it at part load. Second, operators developed techniques to significantly reduce the energy required to start up the turbine. The SOLERGY computer code assumed 10 MWht would be required for start-up. Operations developed the new start-up procedure in October of 1998 and implemented it in November. This resulted in reduction of the required start-up energy to as low as 6.6 MWht. This was a major reason the SOLERGY goal was often exceeded in November.

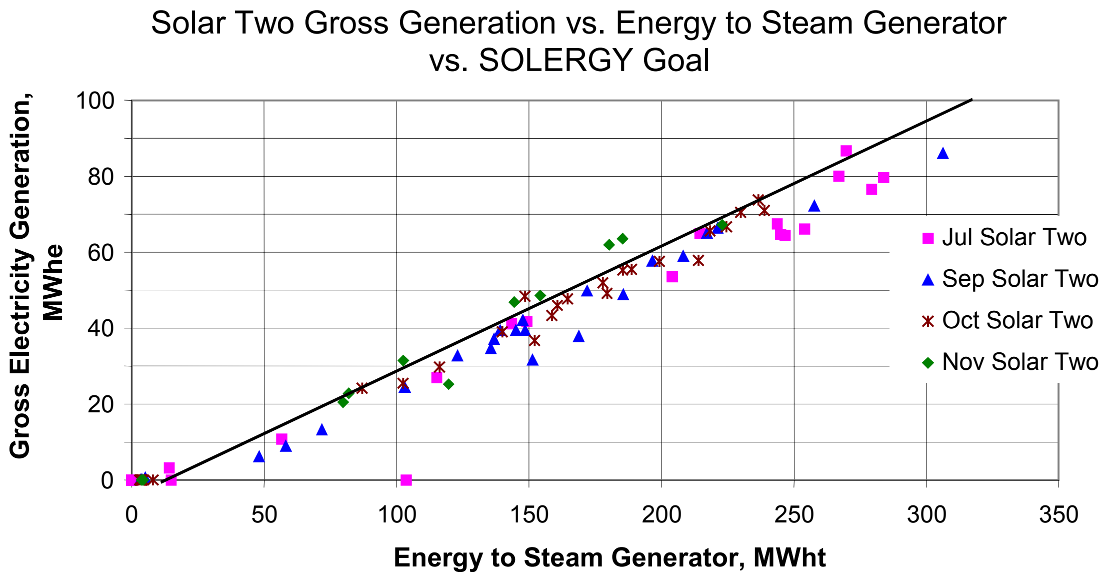

Figure 8. Conversion of Thermal Energy to Electric Energy versus SOLERGY Goal

2.1.4 Conclusions and Recommendations

At design conditions of 655 thousand pounds per hour (kpph) salt flow rate, inlet salt temperature of 1,050 °F and outlet salt temperature of 550 °F, the steam generator was designed to transfer 35.5 megawatts-thermal (MWt) for a gross turbine output of 12 MWe. We were unable to reach the design gross turbine output for several reasons.

First, some cold salt bypassed the receiver and leaked past isolation valves in the SGS. The result was that the inlet salt temperature to the steam generator was degraded. The highest salt temperature going into the steam generator was approximately 1035 °F. Modification of the receiver bypass loop piping and/or isolation valve and replacement of the leaking SGS valves were included in the plans for the Power Production/T&E Phase of the project. These plans were not implemented due to budget restraints and the abbreviated duration of the project.

Second, the steam generator was modified to recirculate saturated water from bottom of the evaporator to the inlet of the pre-heater. This was done to ensure feedwater below the salt freezing point never entered the pre-heater or evaporator during start-up or normal operation. The effect of the recirculation was that the pre-heater had less potential to transfer heat from the salt to the feedwater. A review of the steam generator design and operation is ongoing. Recommendations for the design and operation of the commercial steam generator system will be included in the Final Project Report.

The pre-heater fouling problem was evaluated and was apparently the result of a deficiency in the feedwater chemistry control program. This topic will be discussed in detail in the final report.

The bolted partition plate design for the pre-heater design was reviewed. In a commercial plant design, a welded partition plate was recommended, eliminating the need for a gasket.

Notwithstanding the known system deficiencies, a number of the overall performance goals of the system were demonstrated; specifically:

- Steam generator and turbine-generator performance as a function of flow rate mapped well with predicted performance
- The steady-state gross cycle efficiency of the SGS and the EPGS matched the design value of 34 percent
- The start-up of the SGS and EPGS turbine routinely surpassed the SOLERGY goal – start-up energy usage as low as 6.6 megawatthours-thermal (MWht) was achieved.

The evaluation of the SGS and EPGS also resulted in recommendations for optimization of the design and operation of these systems. They will be presented in the Final Project Report.

2.2 Receiver Efficiency Test – Test 6

2.2.1 Objectives

The major goal of the receiver efficiency test was to map the receiver efficiency as a function of operating temperature and wind speed.

2.2.2 Method

The receiver efficiency, η, is defined as the ratio of the average power absorbed by the working fluid, P_{abs}, to the average power incident on the receiver, P_{inc}, evaluated over a defined period under steady-state conditions.

$$\eta = \frac{\overline{P}_{abs}}{\overline{P}_{inc}} \qquad \text{(Equation 2.2.1)}$$

Two methods were to be used for evaluating the efficiency:

- Complementary heliostat groups (power-on method)
- Receiver heat loss (power-off method).

Testing using the power-off method was not implemented.

2.2.2.1. Power-On Method

The incident power could not be measured directly on this size of receiver; therefore efficiency was to be obtained by eliminating incident power from the heat balance equation and by calculating the thermal losses from known measurements. The power-on method was designed for this type of measurement.

The plant criteria required for this test were:

- The heliostat field availability must be 95 percent or better with any heliostat outages randomly scattered throughout the field.
- The heliostat field must have been biased within the last 3 months.

- The heliostat field cleanliness must be measured within 7 days of the test. If precipitation or a dust storm occurred during the test period, the field cleanliness must be immediately remeasured.
- Receiver system controls must be able to tolerate a 50 percent change in power and achieve steady state within 1 minute.
- The plant must be able to support receiver operation for at least 3 hours at full power.
- The receiver absorptivity must be measured within (before or after) 6 months of the test.

The weather conditions required by this test were:

- Clear sunny day with peak insolation at 800 watts per square meter (W/m^2) or more
- Winds below 5 miles per hour (mph) for one set of tests, between 10 and 20 mph for the second set of tests.

The heliostat field was divided into two groups of equal numbers of heliostats, symmetrically dispersed about the receiver. Group 1 contained every other heliostat. Group 2 contained the heliostats not in Group 1 (Figure 9). The test was conducted symmetrically about solar noon between 11 a.m. and 1 p.m. solar time to minimize cosine effects of the heliostat field.

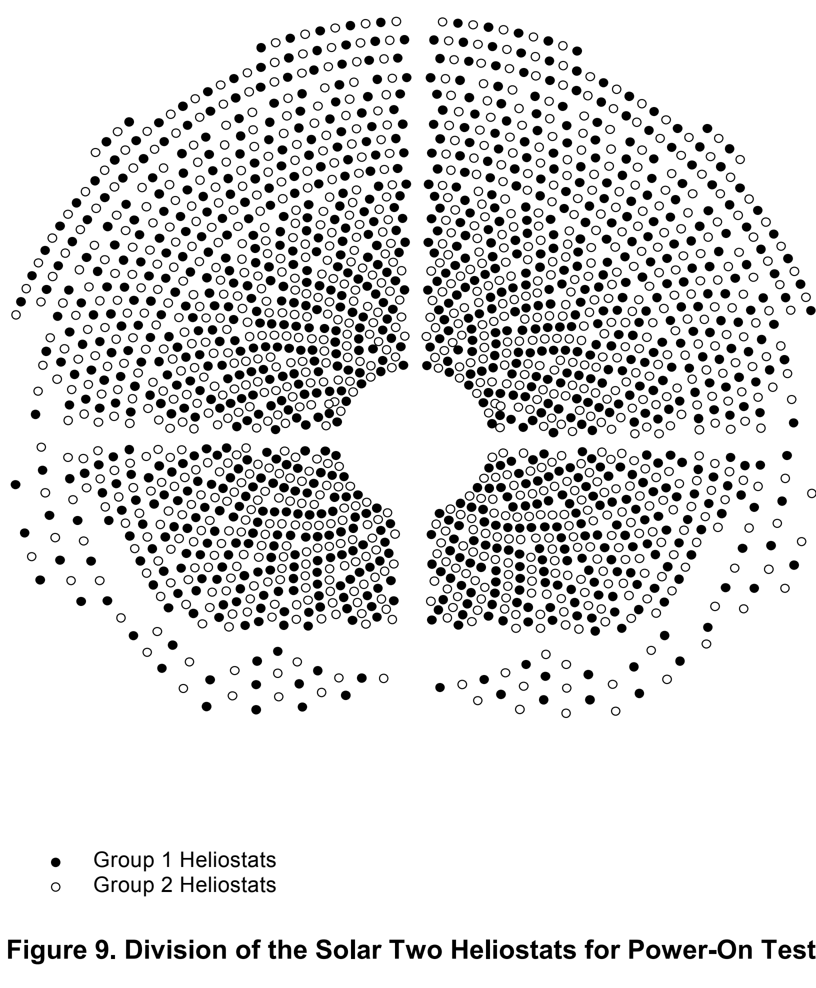

Figure 9. Division of the Solar Two Heliostats for Power-On Tests

The receiver was operated at full power (both groups) with the outlet temperature fixed (e.g., 1,050 °F ±25 °F) during period A, which ran between 11 a.m. and 11:30 a.m. (solar time). For period B, Group 2 heliostats (half the field) were removed (put in standby) and the flow adjusted so the same outlet temperature was achieved. This period ran between 11:30 a.m. and 12 p.m. At 12 p.m., period C started. The flow increased and the full field tracked the receiver again. The flow rate was again adjusted to maintain the same outlet temperature as for the previous periods. At 12:30 p.m., period D began. Group 1 heliostats were removed. The flow rate was adjusted to maintain the desired salt outlet temperature. The test ended at 1 p.m. Table 6 illustrates this sequence.

Table 6. Sequence of Heliostats Tracking the Receiver

Period	Solar Time	Heliostat Group(s)	Incident Power (Available)
A	11:00 a.m. to 11:30 a.m.	1 and 2	100%
B	11:30 a.m. to 12:00 p.m.	1	50%
C	12:00 p.m. to 12:30 p.m.	1 and 2	100%
D	12:30 p.m. to 1:00 p.m.	2	50%

By dividing the heliostat field into two symmetric groups, the power on the receiver can be halved independent of field cleanliness, mirror corrosion, and to some extent heliostat availability. Because of symmetry about solar noon, the average incident power during period A, $P_{inc,A}$, was twice the average incident power during period D, $P_{inc,D}$. Likewise for periods C and B:

$$\overline{P}_{inc,A} = 2\overline{P}_{inc,D} \qquad \text{(Equation 2.2.2)}$$

$$\overline{P}_{inc,C} = 2\overline{P}_{inc,B} \qquad \text{(Equation 2.2.3)}$$

From a heat balance on the receiver during steady-state conditions, the power incident on the receiver equaled the sum of power reflected by the receiver (ρPinc-reflectivity x incident power), the power absorbed by the salt (P_{abs}), and the thermal losses ($L_{thermal}$, radiation, convection, and conduction) from the receiver:

$$\overline{P}_{inc} = \rho\overline{P}_{inc} + \overline{P}_{abs} + \overline{L}_{thermal} \qquad \text{(Equation 2.2.4)}$$

or

$$\alpha\overline{P}_{inc} = \overline{P}_{abs} + \overline{L}_{thermal} \qquad \text{(Equation 2.2.5)}$$

The absorbed power was the mass flow rate of salt times the change in enthalpy of the salt from the inlet to outlet of the receiver:

$$\overline{P}_{abs} = \overline{\dot{m}}(\overline{h}_{T_{out}} - \overline{h}_{T_{in}}) \qquad \text{(Equation 2.2.6)}$$

An important assumption was made:

Under steady-state conditions with constant inlet and outlet salt temperatures and wind velocities, the temperature distributions on the receiver surface and throughout the receiver are independent of power level. Therefore, the thermal losses, $L_{thermal}$, are independent of the incident power.

Although this assumption is not entirely correct (mainly due to the lower heat transfer coefficient of the salt with the tube at lower flow rates), inaccuracies related to it fall well within the uncertainty of the measurements. Consequently, thermal losses can be considered constant.

With constant thermal losses, Equations 2.2.2, 2.2.3, and 2.2.5 can be used to eliminate the incident power.

$$\overline{P}_{abs,A} + \overline{L}_{thermal} = 2\overline{P}_{abs,D} + 2\overline{L}_{thermal} \qquad \text{(Equation 2.2.7)}$$

$$\overline{P}_{abs,B} + \overline{L}_{thermal} = 2\overline{P}_{abs,C} + 2\overline{L}_{thermal} \qquad \text{(Equation 2.2.8)}$$

The thermal loss can then be found. Adding Equations 2.2.7 and 2.2.8 yields:

$$\overline{L}_{thermal} = \tfrac{1}{2}\left(\overline{P}_{abs,A} + \overline{P}_{abs,C} - 2\overline{P}_{abs,B} - 2\overline{P}_{abs,D}\right) \qquad \text{(Equation 2.2.9)}$$

The efficiency can be expressed in terms of the absorbed power, thermal losses, and absorptivity:

$$\eta = \frac{\overline{P}_{abs}}{\overline{P}_{inc}} = \frac{\overline{P}_{abs}}{\dfrac{\overline{P}_{abs} + \overline{L}_{thermal}}{\alpha}} = \frac{\alpha}{1 + \dfrac{\overline{L}_{thermal}}{\overline{P}_{abs}}} \qquad \text{(Equation 2.2.10)}$$

By employing this method, the receiver efficiency can be calculated subject to the uncertainties of the measurements associated with flow rate, inlet and outlet temperatures, and receiver absorptivity. The calculations are averaged over the steady-state portion of each test. Uncertainties of the incident power on the receiver due to the heliostat field performance (such as reflectivity, cosine effects, and alignment) are avoided.

2.2.3 Results

On September 29 and 30, and October 1, 1997, the power-on method was used to measure receiver efficiency. For these tests, the outlet salt temperature was set to 1025 °F instead of 1,050 °F. This reset was in response to concern that the outlet temperature would overshoot the set point when the receiver went through a severe transient. The control system responded well and the temperature overshoot was within the operating limits of the receiver. Performing the test at the de-rated outlet temperature of 1025 °F will result in measured efficiencies about ½ percentage point higher than what would be seen at 1,050 °F. Figure 10 shows the number of heliostats tracking the receiver, receiver salt outlet temperature, salt flow rate, and direct normal insolation during the testing period for the test on October 1, 1997. For these tests, the heliostat availability was greater than 90 percent.

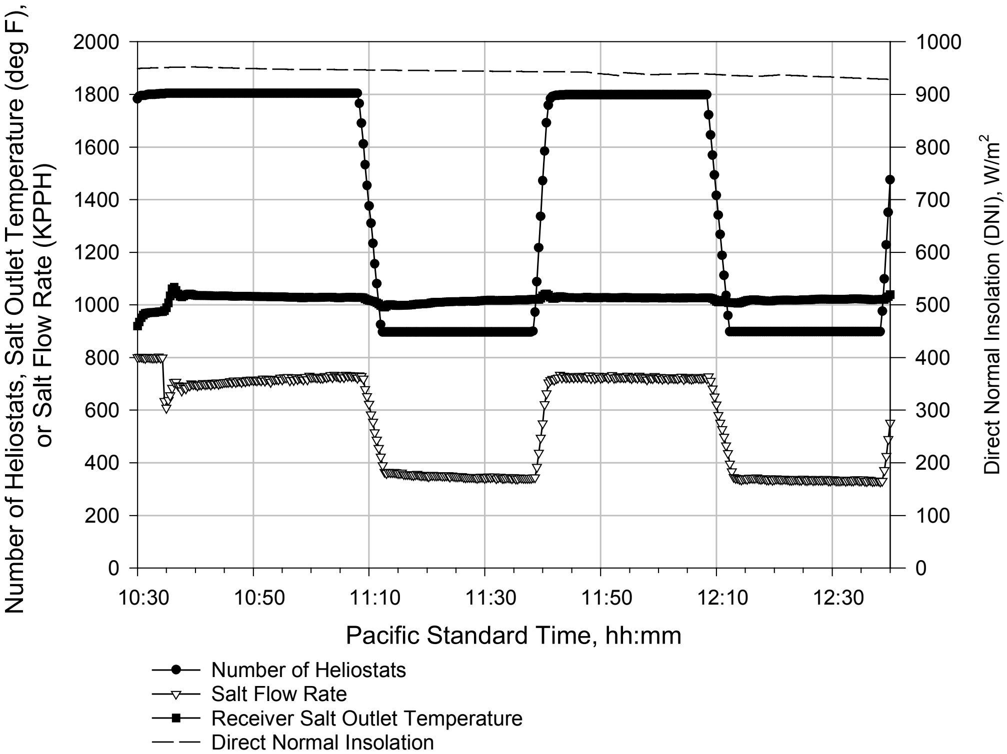

Figure 10. Heliostats Tracking the Receiver, Receiver Outlet Temperature, Salt Flow Rate, and Direct Normal Insolation for the Receiver Efficiency Test on October 1, 1997

The power-on method was again used in March 1999 to measure receiver efficiency. For these tests, the outlet salt temperature was set to the design value of 1,050 °F. The control system did not respond as well as during previous testing. Temperature overshoot during the increased power transient resulted in several receiver high temperature trips. Temperature undershoot and sluggish response were exhibited during the reduced power transient. As a result of the degraded control system response, the March 1999 testing deviated from the original test plan. The individual test periods were increased from 30 to 45 minutes to allow the control system time to stabilize the receiver outlet temperature. The degraded control system response was attributed to the replacement of several receiver photometers. The photometers were replaced by maintenance, but were not calibrated. For these tests, the heliostat availability was 86 to 90 percent.

Table 7 shows a summary of the key data taken over the steady-state portion of the tests. Table 8 shows weather conditions over the steady state portions of the tests.

Table 9 shows average absorbed power, the calculated thermal losses and the receiver efficiency. For the efficiency calculation, a receiver absorptivity of 0.95 was used. This was the measured average receiver absorptivity when the receiver was new. Table 10 shows the time frames in which the steady-state portion of each period occurred. This table also shows when solar noon occurred. Table 11 summarizes the heliostat field cleanliness data The cleanliness of the heliostat field will not affect the receiver thermal efficiency since the receiver efficiency is based on the ratio of absorbed power to incident power on the receiver. The heliostat cleanliness is part of the heliostat field efficiency and not the receiver efficiency.

Table 7. Summary of Key Measurements for Receiver Efficiency Tests

Test Date:	9/29/97	9/30/97	10/1/97	3/5/99	3/12/99	3/17/99	3/22/99	3/23/99	3/24/99
Heliostats Tracking Receiver									
A (full power)	1,767	1,764	1,804	1,668	1,685	1,681	1,699	1,626	1,725
B (half power)	883	883	897	831	853	836	847	809	858
C (full power)	1,76	1,758	1,798	1,664	1,684	1,676	1,692	1,625	1,720
D (half power)	884	876	898	833	830	840	847	805	848
Average Inlet Temperature, °F	**563**	**574**	**581**	**587**	**577**	**575**	**574**	**575**	**569**
A (full power)	560	573	579	591	576	577	573	572	568
B (half power)	564	574	581	591	576	574	572	574	567
C (full power)	565	574	582	585	578	573	575	576	570
D (half power)	565	575	582	582	580	575	577	577	572
Average Outlet Temperature, °F	**1024**	**1023**	**1,023**	**1,047**	**1,046**	**1,047**	**1,045**	**1,041**	**1,047**
A (full power)	1,032	1,026	1,033	1,050	1,047	1,047	1,047	1,046	1,047
B (half power)	1,016	1,018	1,011	1,044	1,042	1,044	1,040	1,037	1,044
C (full power)	1,028	1,030	1,027	1,048	1,048	1,049	1,045	1,047	1,049
D (half power)	1,021	1,017	1,019	1,046	1,047	1,047	1,046	1,034	1,048
Outlet Temperature Setpoint, °F	**1,025**	**1,025**	**1,025**	**1,050**	**1,050**	**1,050**	**1,050**	**1,050**	**1,050**
Average Flow, kpph									
A (full power)	631	716	712	647	531	620	545	481	556
B (half power)	313	338	349	284	252	290	250	219	263
C (full power)	676	720	725	639	577	636	559	514	580
D (half power)	312	344	336	300	262	285	253	236	256

Table 8. Weather Conditions During Receiver Efficiency Tests

Test Date:	9/29/97	9/30/97	10/1/97	3/5/99	3/12/99	3/17/99	3/22/99	3/23/99	3/24/99
Average Wind Speed, Level 7, mph	**1.3**	**2.2**	**1.4**	**6.7**	**4.0**	**3.1**	**2.1**	**17.6**	**3.0**
A (full power)	1.4	2.6	2.1	6.3	4.4	7.1	2.0	20.2	5.5
B (half power)	1.1	3.2	1.5	6.0	4.1	3.1	1.3	19.2	2.2
C (full power)	1.4	1.5	0.9	9.0	4.9	1.0	2.3	15.4	2.1
D (half power)	1.5	1.7	1.0	5.7	2.5	1.3	2.6	15.6	2.1
Wind Direction, Level 7, °F	**131**	**241**	**210**	**270**	**223**	**241**	**165**	**263**	**241**
A (full power)	151	279	256	260	246	267	260	262	277
B (half power)	122	281	231	282	222	275	142	262	269
C (full power)	127	240	216	265	207	206	125	259	187
D (half power)	123	165	139	273	218	217	135	268	232
Direct Normal Insolation, W/m^2	**913**	**975**	**942**	**989**	**898**	**860**	**871**	**874**	**894**
A (full power)	887	975	949	992	865	958	861	858	887
B (half power)	913	977	945	963	879	969	872	869	902
C (full power)	931	976	939	985	915	970	879	875	900
D (half power)	922	971	934	1016	932	944	869	893	889
Average Ambient Temperature, °F	**89**	**91**	**92**	**60**	**58**	**64**	**64**	**60**	**62**

Table 9. Calculated Test Results

Test Date:	9/29/97	9/30/97	10/1/97	3/5/99	3/12/99	3/17/99	3/22/99	3/23/99	3/24/99
Average Absorbed Power, MWt									
A (full power)	31.6	34.4	34.3	31.5	26.5	31.0	27.4	24.2	28.3
B (half power)	15.0	15.9	15.9	13.7	12.5	14.5	12.5	10.8	13.3
C (full power)	33.3	34.9	34.3	31.5	28.8	32.1	27.9	25.7	29.5
D (half power)	15.1	16.1	15.6	14.8	13.0	14.3	12.7	11.4	12.9
Thermal Loss, MWt	**2.27**	**2.57**	**2.75**	**3.04**	**2.18**	**2.76**	**2.55**	**2.75**	**2.63**
Efficiency									
Full Power	0.888	0.884	0.880	0.866	0.881	0.874	0.870	0.856	0.871
Half Power	0.827	0.819	0.809	0.783	0.811	0.797	0.790	0.761	0.792

Note: A receiver absorbtivity of 0.95 was used for these calculations.

Table 10. Time Frames for Steady State Portions of Each Test (Pacific Standard Time)

Test Date:	9/29/97	9/30/97	10/1/97	3/5/99	3/12/99	3/17/99	3/22/99	3/23/99	3/24/99
Steady State Measurement Times, PST									
A Start	10:39:40	10:36:00	10:38:00	11:13:00	10:30:00	10:40:00	11:00:00	10:43:20	10:53:00
A End	11:06:00	11:06:00	11:06:00	11:30:40	11:13:20	11:15:40	11:24:40	11:10:00	11:24:00
B Start	11:18:00	11:17:00	11:15:00	11:37:00	11:24:00	11:25:40	11:35:20	11:23:40	11:33:40
B End	11:36:00	11:36:00	11:36:00	11:54:00	12:00:00	11:56:00	11:52:40	11:55:20	11:53:00
C Start	11:51:00	11:49:40	11:45:00	12:06:00	12:05:40	12:03:00	12:09:00	12:03:00	12:03:00
C End	12:06:00	12:06:00	12:06:00	12:30:00	12:44:40	12:40:40	12:24:40	12:34:00	12:21:40
D Start	12:27:20	12:13:20	12:14:20	12:37:00	12:55:00	12:48:40	12:31:00	12:46:20	12:34:00
D End	12:36:00	12:36:00	12:36:00	13:00:00	13:36:00	13:26:40	12:54:00	13:19:20	12:53:20
Solar Noon	11:36	11:36	11:36						

Table 11. Field Cleanliness Measurements

Measurement Date	9/30/97	2/27/99	3/8/99	3/17/99	3/26/99
Martin Field	**Cleanliness**				
Northeast	97.67%	94.21%	90.50%	92.71%	94.26%
Northwest	96.99%	95.47%	90.67%	93.66%	94.82%
Southeast	95.16%	95.97%	91.20%	93.78%	94.34%
Southwest	96.90%	96.26%	92.55%	94.06%	92.31%
Lugo Field	**Cleanliness**				
LSE	92.43%	84.61%	68.39%	87.76%	No data
LSW	93.34%	83.79%	73.09%	87.57%	No data

2.2.4 Conclusions and Recommendations

An uncertainty analysis of the receiver efficiency based on estimates of the measurement uncertainties of the instruments was conducted. Table 12 summarizes the uncertainty for each measurement.

Table 12. Measurement Uncertainties for Receiver Efficiency Testing

Measurement	Uncertainty
Temperature	±5 °F, over 500 °F span is ±1%
Flow Rate	±1% (random uncertainty)
Absorptivity (α)	+0.00/-0.02, this corresponds to +0.0%/-2.1% at α = 0.95
Heliostat Tracking Repeatability	±5 heliostats, or 5/1,800 = 0.3%

Uncertainty in the flow measurement is based on the random uncertainty (scatter at a constant flow rate) and not slope or offset uncertainty. The reason for this is that the power-on test is a back-to-back comparison that depends on differences of parameters over a time period too short for significant calibration drift. As confirmed in Equation 2.2.10, the efficiency is based on the ratio of the thermal loss (Equation 2.2.9) to the absorbed power (Equation 2.2.6). Even if the slope of the calibration curve of the mass flow rate is off significantly (say 10 percent), the error due to this will divide out. The errors that do affect the measurement are offset and random scatter. The data show that the offset during no flow is very small (around 0.5 kpph). The random scatter under steady-state portions of the experiment is approximately 6.0 kpph. The sum of the these uncertainties is 6.5 kpph which is <1 percent at full flow.

Using the values in Table 12, the receiver efficiency uncertainty, based on the root-sum-square value (95 percent confidence) is:

$$\in_{\eta} = +(1^2 + 1^2 + 0^2 + 0.32)^{0.5} = +1.4\% \qquad \text{(Equation 2.2.12)}$$

$$\in_{\eta} = -(1^2 + 1^2 + 2.1^2 + 0.3^2)^{0.5} = -2.5\% \qquad \text{(Equation 2.2.13)}$$

For an efficiency of η=0.884, the true value of the receiver efficiency at 95 percent confidence is:

$$\eta = 0.884 + 0.012/\text{-}0.022 = 0.862 \text{ to } 0.896 \qquad \text{(Equation 2.2.14)}$$

Prior to conducting the receiver efficiency test on September 25, 1997, receiver manufacturer Boeing North American, Inc. verbally provided an estimate of the receiver efficiency as a function of wind speed. Table 13 summarizes their estimate, which is based on the full power output of the heliostat field which results in a receiver incident power of 48.6 MWt, receiver salt inlet and outlet temperatures of 550 °F and 1,050 °F, respectively, and a receiver absorptivity of 0.95. The efficiency calculation does not account for the additional loss from the back of the receiver due to convection. This amounts to approximately 300 kilowatt (kW) or a drop in efficiency of 0.005. The salt temperature measurements are based on the temperature of the salt entering the first panel and exiting the last panels. It does not include the effect of cold salt leaking past the receiver diversion valve to the downcomer.

Table 13. Predicted Receiver Efficiency as Function of Wind Speed for Incident Power of 48.6 MWt

Wind Speed at 10 meters, mph	Receiver Thermal Efficiency
0	0.89
11.6	0.88
30	0.86

A model of the thermal performance of the receiver was used to estimate the efficiency at the test conditions [2]. This model does a heat balance on the receiver accounting for losses due to reflection, radiation, convection, and conduction. It employs the mixed convection correlation proposed by Stoddard [3]. The receiver model accurately predicted the receiver efficiency as a function of wind speed within 1 percent.

Receiver efficiency, under calm wind conditions, was measured to be 88 percent, which was within 1 percent of Boeing's prediction.

Table 14 compares model results to the test results. These predicted results fall within the uncertainty of the instruments for the measured results. A plot of the effect of wind speed and incident power on the receiver efficiency was generated using the model and is shown in . To calculate the wind speed at a different height, the wind velocity, V, is: $V = V_{10\ meters}(h/10)^{0.15}$, where h is the height in meters. At high incident powers, the effect of wind is relatively minor.

Table 14. Comparison of Predicted Efficiency (From Model) With Measured Efficiency

Test Date:	9/29/99	9/30/99	10/1/99	3/5/99	3/12/99	3/17/99	3/22/99	3/23/99	3/24/99
	Efficiency								
Predicted Full Power	0.877	0.881	0.880	0.866	0.881	0.874	0.870	0.856	0.871
Measured Full Power	0.888	0.884	0.880	0.872	0.865	0.874	0.866	0.839	0.869
Difference	**-0.011**	**-0.003**	**0.000**	**0.006**	**-0.016**	**0.000**	**-0.004**	**-0.017**	**-0.002**
Predicted Half Power	0.815	0.822	0.820	0.783	0.811	0.797	0.790	0.761	0.792
Measured Half Power	0.827	0.819	0.809	0.801	0.791	0.807	0.790	0.740	0.794
Difference	**-0.012**	**0.003**	**0.011**	**0.018**	**-0.020**	**0.010**	**0.000**	**-0.021**	**0.002**

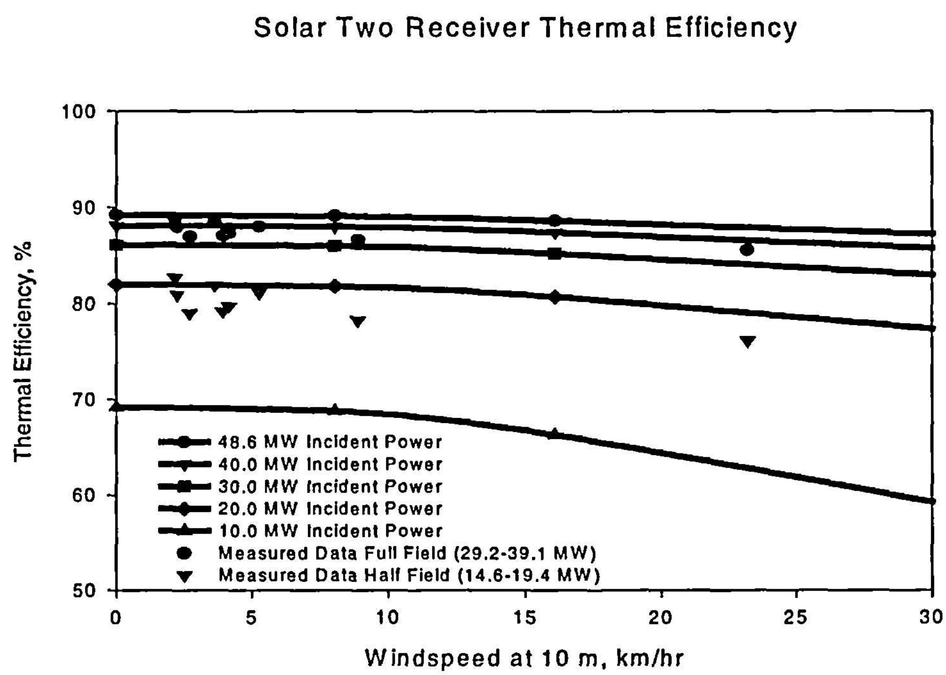

Figure 11. Receiver Efficiency as a Function of Wind Speed (Measured at 10 m) at Various Incident Powers Along With Measured Receiver Efficiency Data

Recommendations for the design of the receiver for the commercial plant will be included in the Final Project Report.

2.3 Thermal Losses Throughout the Plant – Test 8

2.3.1 Objectives

The objective of this test was to measure the thermal losses of the major Solar Two components due to convection, conduction, and radiation. The information obtained will be used to develop a detailed heat balance for the plant and acquire the data required to design a thermally efficient commercial plant.

2.3.2 Methods

Two methods were employed to acquire the data necessary to determine the component and system heat losses at Solar Two:

- **Isothermal Testing** – During a plant shutdown, the heat tracing and immersion heater power consumption was monitored as they maintained the vessels and components at a constant temperature.
- **Cool Down Testing** – During a plant shutdown, shut off all heat tracing and immersion heaters. Monitor the installed temperature sensors to determine the mean temperature of the components. Using measured temperature data, calculate the component and system heat losses.

Note: The thermal losses of the steam generator will be determined as part of Test 3.

2.3.3 Results

On April 2 and 3, 1997, a precursor test was performed by Bechtel with participation of the T&E Team. In this test, the receiver system was drained and all heat trace associated with receiver equipment provided by Rocketdyne (equipment near top of tower) was turned off for a period of 18 hours. During the 18-hour period, pipes, vessels, and valves were allowed to cool. Most equipment was near ambient temperature at the end of the period (except for the surge vessels, which cooled to approximately 300 °F). The heat trace was then turned on and the equipment was returned to operating temperature. Table 15 provides the times required to return the equipment to 500 °F.

Table 15. Acceptance Criteria for Receiver Heat Trace Test

Valves	≤4 hrs
Insulated Pipes	≤2 hrs
Inlet and Outlet Surge Vessels	≤1 hr
Upper Headers Heated by Oven	≤2 hr
Lower Headers Heated by Oven	≤2 hrs

A cursory evaluation of the results of this test was performed. The review showed that a vast majority of the components, but not all, satisfied the acceptance criteria. Similar tests were performed on the remainder of the plant during the test period. The data from these tests are currently being evaluated. The only results available at this time are for the salt storage tanks and sumps. Table 16 presents the results. All of the losses are essentially as predicted except for the Steam Generator Sump. The higher than expected Steam Generator Sump losses are believed due to damaged insulation. During the Start-up Phase, a salt leak saturated the sump's insulation and reduced its effectiveness.

Table 16. Measured and Calculated Thermal Losses Tanks and Sumps

Major Equipment	Calculated Thermal Loss, kilowatts-thermal (kWt)	Measured Thermal Loss, kWt
Hot Salt Tank at 1,050 °F	98	102
Cold Salt Tank at 550 °F	45	44
Steam Generator Sump at 1,050 °F	14	29
Receiver Sump at 550 °F	13	9.5

2.3.4 Conclusions and Recommendations

The measured heat loss associated with the Solar Two thermal storage system during steady state conditions was within 8.5 percent of the predicted values. Measured heat loss was only 185 kilowatt, which, on an annual basis, corresponds to approximately 1 percent of the total energy supplied to the thermal storage system. This allows for efficient storage of thermal energy. Based on these results, it is expected the annual efficiency of the thermal storage system in a commercial plant should be >99 percent. This information will be used to develop a detailed heat balance for the plant and acquire the data necessary to design a thermally efficient commercial plant. Figure 12 shows the thermal storage steam and generator systems.

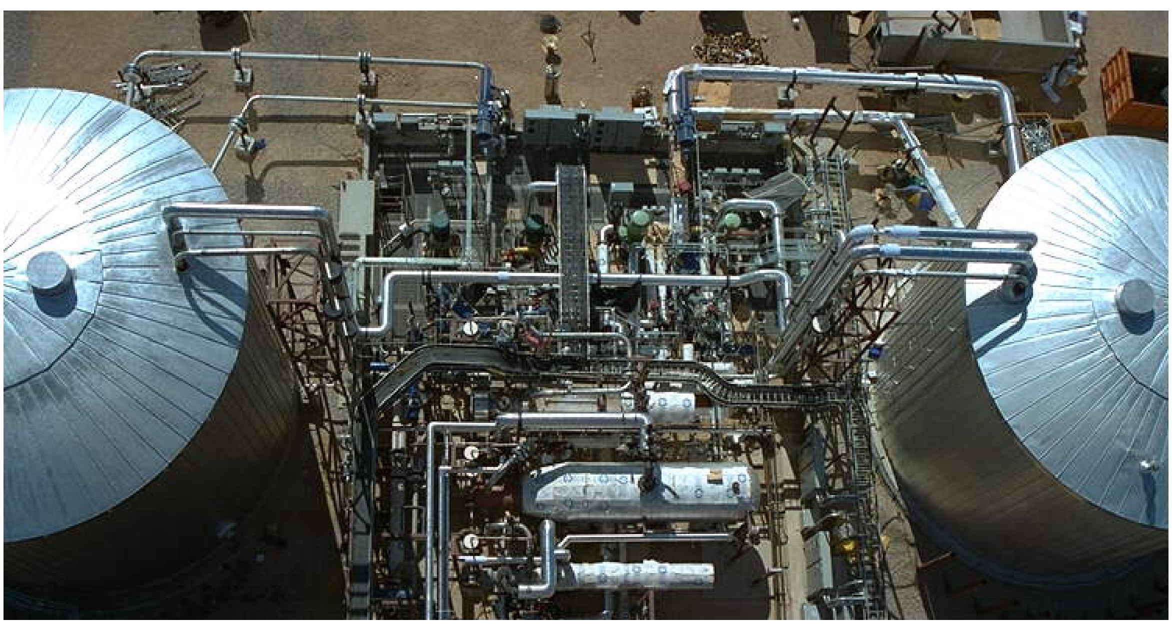

Figure 12. Solar Two Thermal Storage Steam and Generator Systems

2.4 Parasitic Power Consumption – Test 9

2.4.1 Objectives

The objective of this test was to determine the electric power consumption throughout the plant as a function of operating state. The data was to be used to minimize parasitic power consumption and assist in the optimization of overall plant performance.

2.4.2 Method

Power consumption was directly or indirectly monitored for all major plant components and load centers. Table 9-1 of Appendix I provides a list of equipment originally chosen for monitoring. A priority was assigned to each of these items based on expected contribution to the total plant parasitic load.

2.4.3 Results

During the first 7 months of 1998, electrical power consumption was monitored at the load center level. The values obtained were compared with design data and SOLERGY predictions. Load centers with obviously high electrical consumption were analyzed in greater detail. In early August of 1998, a number of suggestions for methods to reduce the parasitic loads were proposed. Primary among these were:

- The use of a circulating water jockey pump when the plant was in Short Term Hold
- Implementation of the first phase of the Overnight Thermal Conditioning Test – heat trace circuits were essentially turned off at the end of the day's operation and turned on prior to the next day's start-up.

These measures were completely implemented by late September of 1998. Figure 13 and Figure 14 present the results of these initial parasitic load reduction efforts. In Figure 13, the solid line represents the SOLERGY predicted values. The trend of the data from July through November shows a reduction of approximately 27 percent in the typical daily parasitic load.

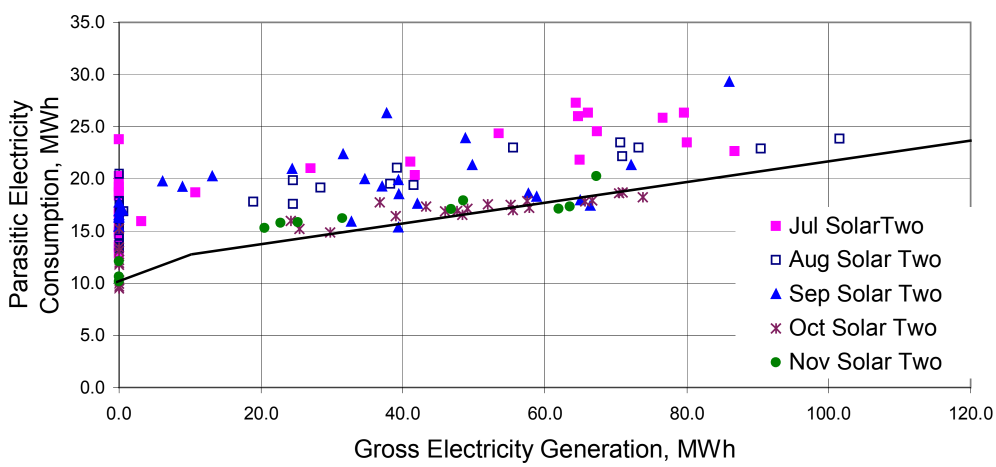

Figure 13. Parasitic Electricity Consumption as a Function of Gross Generation

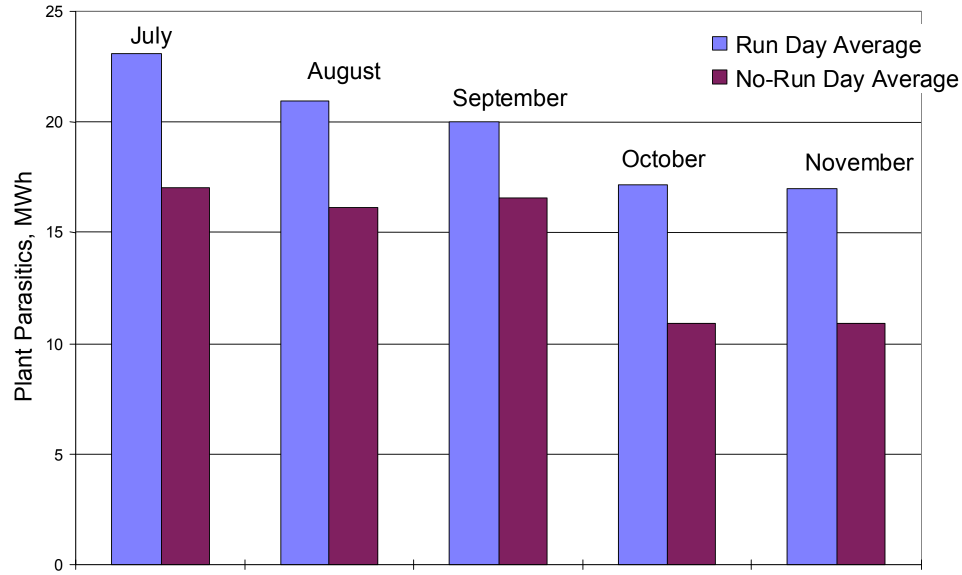

Figure 14. Average Solar Two Parasitic Power Consumption for Run and No-Run Days

2.4.4 Conclusions and Recommendations

The daily parasitic power consumption was initially found to be 23 megawatthour (MWh). Measures to reduce parasitic power consumption were identified and introduced during August and September 1998. Major problem areas identified were the excessive operation of heaters, pumps and other auxiliary equipment. By optimizing the use of the heaters, pumps and auxiliary equipment, a 27 percent reduction in parasitic power consumption was experienced.

A number of additional measures to reduce parasitic power consumption were planned, but could not be implemented prior to the shutdown of the Solar Two Project. The reduction experienced, however, demonstrated that the goals established by the SOLERGY code could be met. It is recommended that the data resulting from this effort be used to minimize parasitic power consumption and assist in the optimization of overall plant performance for commercial facilities. Additional discussion of the test results and recommendations for the commercial plant will be included in the Final Project Report.

2.5 Dispatchability – Test 16

2.5.1 Objectives

The dispatchability test demonstrated one of the distinct advantages of a molten-salt power tower plant; its ability to collect solar energy when the sun shines and store this energy until it is used to produce steam to spin a turbine/generator. The dispatchability test demonstrated Solar Two's ability to generate dispatchable (i.e., on-demand) power from solar energy stored in the molten salt.

The objective of this test was to determine the capability of the plant to dispatch power for different periods of time in differing conditions (through out the day, through clouds, and in the night). The specific goals of this test were to:

- Determine the capability of the plant to dispatch power for different periods of time
- Provide a matrix of average power produced for specific dispatch periods, noting ambient weather conditions
- Dispatch stored heat at different times of the day and night, to identify effects on operating procedures and unexpected changes in plant efficiency
- Document the lessons learned and, as applicable, recommend changes to design and operation.

2.5.2 Methods

Other tests have demonstrated the separate operation of the energy collection and power production systems. The dispatchability test demonstrated the flexibility of meeting a wide range of load-shifting requirements. For example, by operating the power production system at reduced power output levels, Solar Two's 3-hour, full-load storage capacity will be used to demonstrate the equivalent of a 6-hour storage system. This was expanded in June and July of 1998 to demonstrate continuous power production for extended periods of time.

2.5.3 Results

Three operational periods were originally used to demonstrate Solar Two's dispatchability. These were:

- November 1, 1996 – Dispatchability After Dark
- November 5, 1996 – Dispatchability Through Heavy Clouds
- November 6, 1997 – Dispatchability Throughout the Day.

Note that the last data was for a period 1 year after the first two data sets. The following paragraphs describe each of these operating periods and the dispatchability results obtained.

November 1, 1996 – Dispatchability After Dark

This test sequence occurred prior to the evaporator tube rupture on November 7, 1996, and the subsequent repairs, modifications and improvements to the evaporator system. Figure 15 provides a plot of the day's solar insolation, receiver power, and gross electric power. The data reflect the early state of operations in the fall of 1996, as evidenced by the short receiver operating day; the EPGS dropout for an hour after approximately 15 minutes of power production; and the low EPGS output levels (approximately 5 MWe gross), resulting from the unavailability of the extraction steam/feedwater heater system. However, the data sequence is a classic example of Solar Two's dispatchability. Solar energy was collected for approximately 2.5 hours during the middle of a nearly flawless solar day. The EPGS was heated and brought to operating conditions so that, as the sun set, the turbine was synchronized and delivered power to the grid for approximately 1 hour and 45 minutes.

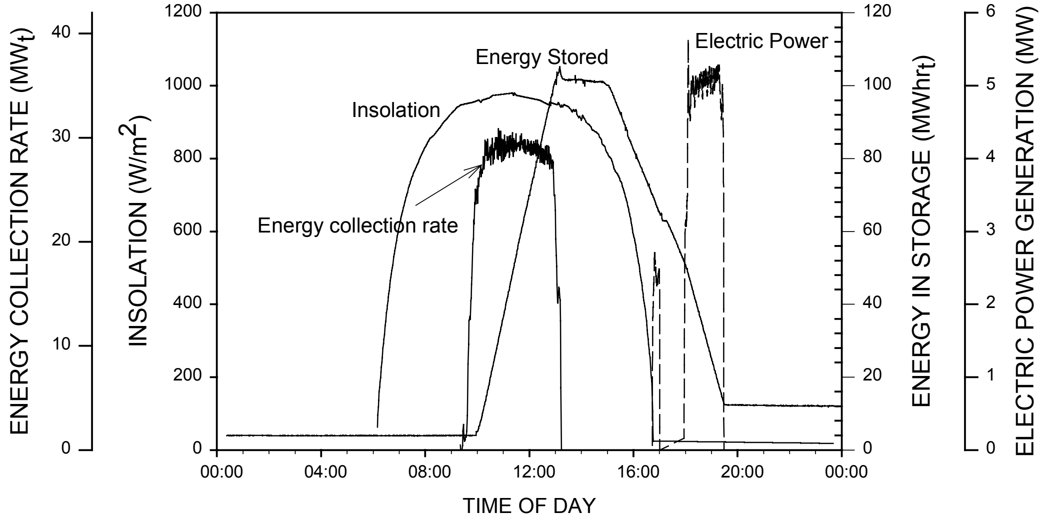

Figure 15. Electric Energy Dispatching at Solar Two on November 1, 1996

November 5, 1996 – Dispatchability Through Heavy Clouds

Figure 16 shows the data for this day, which were also were recorded just prior to the evaporator tube rupture. The receiver was brought to operating power levels at approximately the same time as on November 1, 1996, and was still operating when the insolation dropped off in the early afternoon due to heavy cloud cover. The generator was synchronized and delivered power to the grid as the receiver energy collection ended. The turbine again operated at slightly under the 5 MWe level.

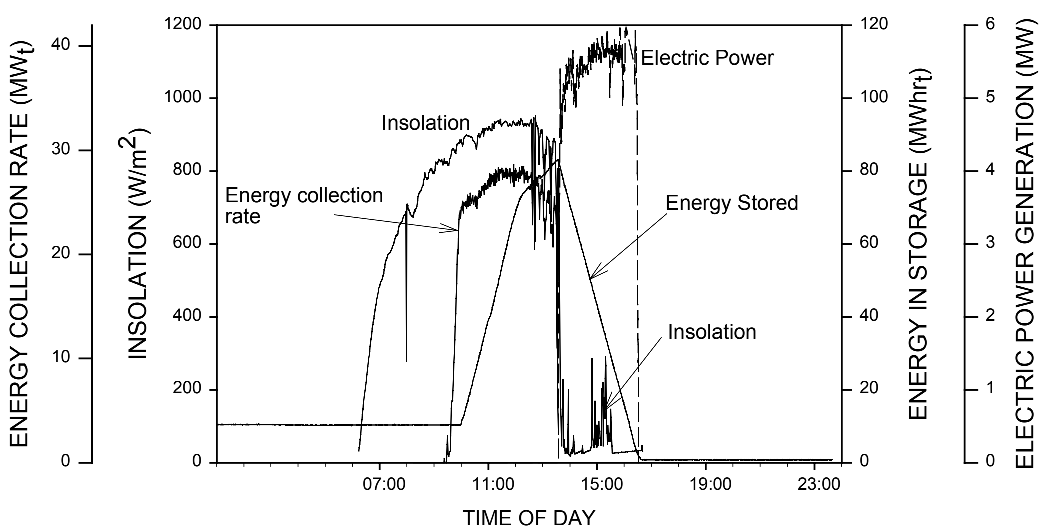

Figure 16. Electric Energy Dispatching at Solar Two on November 5, 1996

November 6, 1997 – Dispatchability Throughout the Day

The steam generator system had been redesigned and repaired well before operation on November 6 (Figure 17). A successful run of the receiver system the previous day had filled the hot salt tank with salt at approximately 1010 °F. This stored energy allowed operators to start turbine operations early in the morning. As the sun rose and solar insolation climbed, the operators brought the receiver on-line and started recharging the hot salt tank with hot salt. The turbine/generator was synchronized to the grid at 08:23 and produced power until it was taken off-line at approximately 16:15. In parallel, the receiver was brought to operate mode at 08:00 and produced hot salt until heliostats were removed at 15:45. Although power was not produced after dark, these data indicate the ability to uncouple (within the limits of the plant's storage capacity) the energy collection and power production functions.

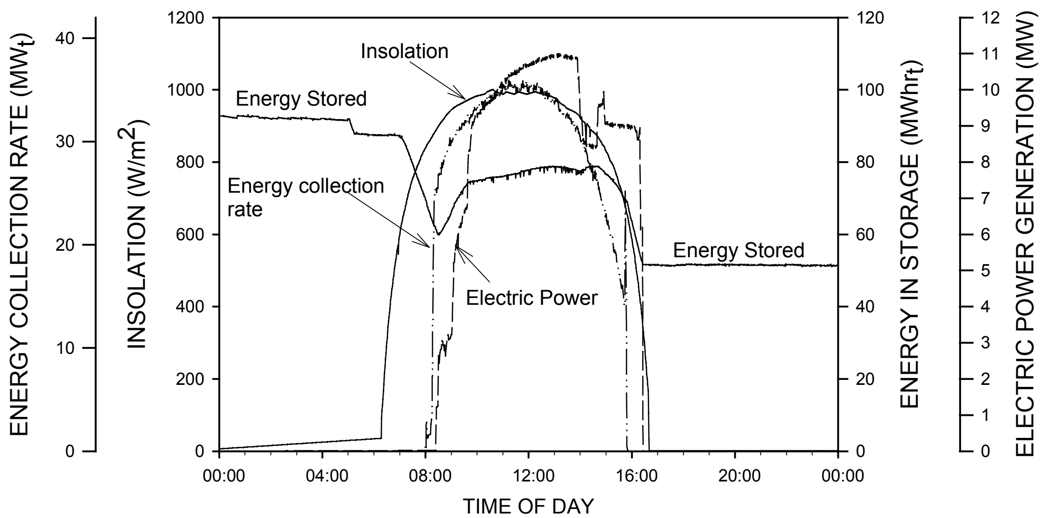

Figure 17. Electric Energy Dispatching at Solar Two on November 6, 1997

In June and July of 1998, two operational periods were used to demonstrate that solar-only power could be continuously delivered to the grid for extended periods of time.

- **June 1998 – 69 hours and 45 minutes** – The turbine was synchronized to the grid at 12:41 Pacific Daylight Time (PDT) on June 13, 1998, and continuously delivered power to the grid until 10:26 PDT on June 16, 1998.
- **July 1998 – 153 hours** – The turbine was synchronized to the grid at 10:15 PDT on July 1, 1998, and continuously delivered power to the grid until after 19:00 PDT on July 7, 1998.

2.5.4 Conclusions and Recommendations

Operation of the Solar Two Plant successfully demonstrated the versatility of a molten-salt power tower system. The plant demonstrated its ability to routinely produce electricity through heavy clouds, after sunset, and throughout the day. During one test, the plant produced electricity, around-the-clock, for 153 consecutive hours (nearly 1 week). This demonstrated the potential to dispatch power independently from the collection of energy from the sun. This test demonstrated that a molten-salt power tower plant can be designed to satisfy a wide variety of power demand profiles by varying the size of the collection system and the total salt storage size. Lessons learned from this testing can be used to improve design and operation of commercial plants.

3.0 Evaluations

Evaluation results for the contract period follow.

3.1 Performance Evaluation

3.1.1 Objectives

The objective of Solar Two's performance evaluation activity is to understand the plant's performance and to use the evaluation information for the following purposes:

- Optimize plant performance
- Extrapolate Solar Two's performance to general performance of molten salt central receiver technology
- Recommend revisions to predictive models and engineering design methods for Solar Two and future generation molten salt central receiver technology.

The primary aspect of the performance evaluation is the lost electricity analysis. This analysis compares the actual generation with the generation predicted by the Solar Two model. SOLERGY, a computer program developed by Sandia National Laboratories to simulate the operation and power output of a solar central receiver power plant is the code used to model Solar Two. The difference between the predicted and the actual generation (i.e., the lost electricity) is broken down into the different efficiency and availability categories responsible for the loss. Having the losses broken down by system and in terms of electricity is useful for understanding and improving the plant's performance; it provides a tool for determining the best operating procedures for plant performance and the allocation of operation and maintenance resources for the best performance payback.

3.1.1.1. Nomenclature

The nomenclature used throughout this section is defined as follows:

E_{INC}	Daily incident thermal energy, kilowatt-hour (kWhr). This is the daily-integrated direct normal solar radiation multiplied by the total heliostat field reflective area.
$E_{UNAVAIL}$	Daily incident thermal energy during times that salt is not flowing through the receiver and SOLERGY indicates that the receiver should be in operation, kWhr.
E_{AVAIL}	Daily incident thermal energy during times that salt is flowing through the receiver, kWhr.
%AreaTracking	Daily fraction of field area that tracked the receiver.
Clean	Cleanliness of the field, as measured throughout the month by the plant maintenance crew.
η_{FIELD}	General field efficiency. Includes reflectivity, cosine loss, and spillage.
η_{REC}	Receiver efficiency.

E_{COLL}	Daily thermal energy collected by the receiver and transferred to the working fluid, kWhr.
η_{TS}	Loss factor for energy passed through thermal storage and the heat transport piping. Defined as the ratio of the thermal energy collected on the salt side of the steam generator system (SGS) to the thermal energy collected by the receiver throughout the month. Includes the effect of thermal energy consumed during short-term hold by the SGS.
E_{TOSGS}	Daily thermal energy sent to the steam generator for warm-up and power production, kWhr.
$\eta_{SGS/EPGS}$	Combined thermal efficiencies of the SGS and the electric power generation system (EPGS).
E_{GROSS}	Daily gross electric energy generated, kWhr.
E_{PARA}	Daily electric parasitic energy, kWhr.
E_{NET}	Daily net electrical energy generated, kWhr.

3.1.2 Methods

The precise modeling of Solar Two performance is important to optimize plant performance. It is also an integral part of extrapolating the plant performance evaluation to the general performance of molten salt central receiver technology. One way Solar Two data will assist in developing future generation molten salt central receiver technology is by helping to develop accurate modeling techniques for the technology. Significant uncertainties still exist, however, in the performance modeling of the plant. An important aspect of the performance analysis is that disagreement between predicted and actual plant performance may not be due to inadequacies on the part of Solar Two, but rather inaccuracies on the part of the SOLERGY model. The primary causes of these inaccuracies are due to uncertainties associated with the following:

- Energy losses from the receiver due to the wind
- Calibration of instrumentation (primarily flow meters)
- Degradation of the heliostat field
- Heliostat tracking errors
- Modeling of the plant parasitics
- Realistic operating patterns resulting from the plant's "human element."

As more of the Solar Two operating experience is evaluated and the performance evaluation progresses, Solar Two data will become useful for future generation central receiver technology designs. A significant portion of the evaluation will be to examine which Solar Two operating procedures and equipment types best accommodate optimized performance. These procedures and equipment types will become part of future designs. Operating procedures and equipment not conducive to optimizing plant performance should be reviewed for exclusion from potential plant designs.

3.1.2.1. Method of Lost Electricity Analysis

The primary aspect of the performance analysis is the lost electricity analysis, which is summarized on a monthly basis. The analysis treats the gross electricity generation predicted by the model as the design performance level for the plant. Any difference between the design performance (modeled values) and the actual performance (measured values) is translated into lost electricity.

$$\text{Losses} = \text{SOLERGY Prediction} - \text{Solar Two Performance}$$

The results are useful in determining which operating procedures are best for plant performance and where to get the best return, in terms of power generation, on plant operation and maintenance resources.

Because the SOLERGY prediction is based on an ideal, design level performance for the plant's current configuration, and because the Solar Two design was still being debugged and operation was not yet fully optimized, Solar Two's actual performance was generally (but not always) lower than the SOLERGY prediction. The convention in this documentation is if Solar Two underperformed relative to the model, the calculated losses are positive. If Solar Two outperformed the model, all equations here are still valid but losses become negative.

The final product of the analysis is the calculated difference between the actual and predicted gross generation. The difference (i.e., the lost electricity) is broken down into the different efficiency and availability categories responsible for the loss. The steps that lead up to this final product, are defined in the following.

Step 1. Calculate and Process Actual Plant Performance

The plant data that are used in the lost electricity analysis are:

- Insolation
- Wind speed
- Heliostat field cleanliness
- Heliostat field availability
- Energy to the working fluid in the receiver
- Energy to the SGS
- Gross electricity from the turbine.

The weather data and the gross electricity are metered directly at Solar Two. The actual weather data is used as input to the SOLERGY model. The energy to the working fluid and the energy to the SGS are calculated from actual plant data. The energy to the working fluid is used to determine whether or not the actual solar plant thermal delivery matches the design. The energy to the steam generator and the gross electricity are used together for power plant efficiency calculations. All plant performance data are processed over 5-minute intervals with the exception of the weather data, which are processed in 15-minute intervals for SOLERGY.

Step 2. Calculate SOLERGY Predicted Performance

Using a given month's actual weather data, a SOLERGY model of Solar Two is run to calculate the design performance of the plant in terms of energy to the working fluid, energy to the steam generator, and the gross electricity from the turbine.

Important SOLERGY assumptions for the analysis are:

- 98 percent heliostat field availability
- 95 percent field cleanliness, corresponding to heliostat field washing on a 2-week cycle
- Heliostats are canted and tracking properly
- Heliostat field efficiency includes what we know about existing mirror corrosion.

Using these assumptions in the model does not necessarily mean these values agree with actual plant conditions. Rather, their use results in a metric that describes what the collector system should be able to achieve. By design, 98 percent of the heliostats should be available for tracking the receiver. If the heliostat field availability is below 98 percent, the actual thermal collection will be lower than the predicted value. To bring the performance up to the design level, the heliostat field availability would need to be improved. All of the SOLERGY input values are based on values thought to be achievable after optimization is complete, given the plant's design configuration.

SOLERGY data inputs and outputs are on a 15-minute time interval. When finer time intervals are required for comparing the SOLERGY output with the actual data, the analysis does a linear interpolation between the SOLERGY points. The SOLERGY run spans the entire month, but each day's performance is examined separately.

Step 3. Determine When Plant Was and Was Not Available for Operation

This is the first step in distinguishing between availability losses and efficiency losses. The analysis begins by examining the actual and modeled energy to the working fluid on a 5-minute basis. It determines at which times the Solar Two receiver was operating and the SOLERGY model determined it should have been and at which times the Solar Two receiver was not operating but the model determined it should have been. If both the actual and the modeled energy to the working fluid are nonzero for a 5-minute time span, the plant is classified as available during that time span. If, on the other hand, the actual energy to the working fluid is zero and the modeled is nonzero, the plant is classified as unavailable during that time span.

For isolating times when the plant was unavailable, the assumption is that all Solar Two plant availability problems will either immediately or eventually force the receiver to become unavailable. For example, an SGS unavailability significant enough to cause a loss in gross generation (as opposed to just a slight shift in the generation profile) will result in a loss of receiver availability once the hot storage tank is full and there is no more cold salt to run through the receiver. This example illustrates why it is necessary to examine the energy to the working fluid as part of the lost electricity analysis. Without looking at the energy to the working fluid, it could not be determined if a problem with the SGS caused a generation loss due to availability (i.e., shut down receiver operation) or just caused a slight delay in electricity generation.

Figure 18 illustrates the methodology for this portion of the analysis. Figure 18 is a plot of the actual and predicted power to the working fluid for 1 day in March 1998. The total area under the curve represents the predicted energy collection for the day. The area labeled $E_{UNAVAIL}$ represents the predicted energy to the working fluid when the plant was not operating. The area labeled E_{AVAIL} represents the actual energy to the working fluid, which in this example is being collected during a time of predicted energy collection. Thus the plant was available during the time span indicated by the area labeled E_{AVAIL}.

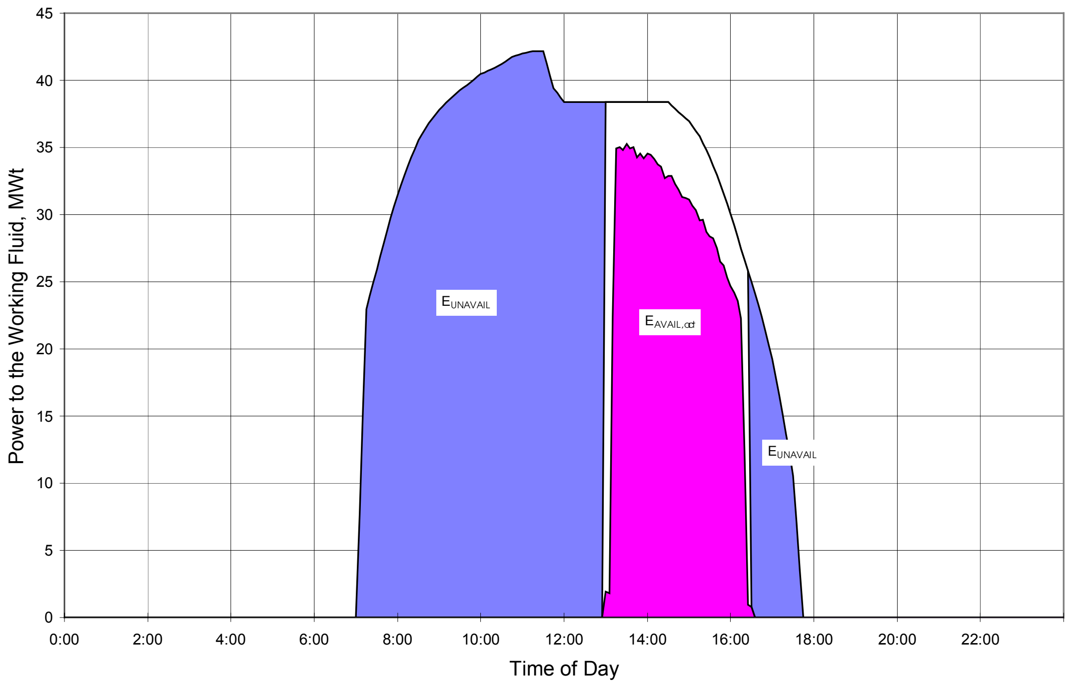

Figure 18. Energy to the Working Fluid – Available and Unavailable Time Spans for Solar Two

It should be noted that times when the receiver was operating and SOLERGY predicted it should not have been, are classified as times when the plant's performance beat the design level performance. These times are tracked and reported in a category separate from the available and unavailable categories.

Step 4. Attribute Losses

The last step in the analysis breaks down the plant/system losses into different categories. The loss analysis begins with the energy incident on the heliostat field and tracks that energy through the plant to generated electricity. Figure 19 illustrates this analysis path in the flow diagram.

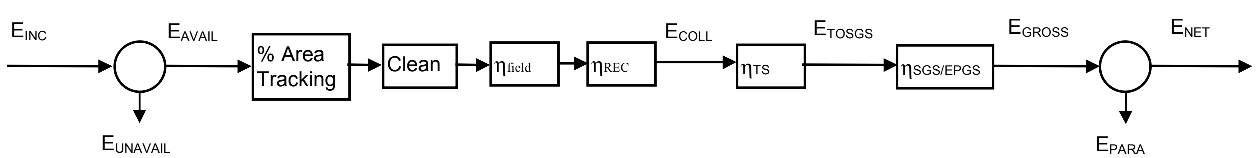

Figure 19. Energy Flow Diagram for Solar Two Lost Electricity Analyses

Figure 19 shows the mathematical relationship for the energy flow, as follows in Equation 3.1.1:

$$E_{GROSS} = (E_{AVAIL})(\%AreaTracking)(Clean)*(\eta_{FIELD})(\eta_{REC})(\eta_{TS})(\eta_{SGS/EPGS}) \quad \text{[Equation 3.1.1]}$$

All of the terms in Figure 19 can be calculated from plant data except for $E_{UNAVAIL}$ and E_{AVAIL}, which require SOLERGY results. The receiver efficiency, η_{REC}, has been measured by testing and is documented in Section 2.2 of this report.

The sensitivity to a change in each term on the right hand side of Equation 3.1.1 on the gross electrical production, E_{GROSS}, can be estimated by taking the partial differential of E_{GROSS} with respect to that term. That is:

$$\text{Sensitivity to Change in } E_{AVAIL} = \frac{\partial E_{GROSS}}{\partial E_{AVAIL}} = -(\%AreaTracking)(Clean)(\eta_{FIELD})(\eta_{REC})(\eta_{TS})(\eta_{SGS/EPGS}) \quad \text{[Equation 3.1.2]}$$

And the energy lost due to a difference in the factor relative to the SOLERGY model can be estimated by multiplying the sensitivity by the magnitude of the change in the factor.

Energy lost due to fewer heliostats tracking than predicted:

$$E_{LOSS,\%TRACK} = (E_{AVAIL})(Clean)(\eta_{FIELD})(\eta_{REC})(\eta_{TS})(\eta_{SGS/EPGS})\Delta\%AreaTracking \quad \text{[Equation 3.1.3]}$$

Energy lost due to soiled heliostats:

$$E_{LOSS,CLEAN} = (E_{AVAIL})(\%AreaTracking)(\eta_{FIELD})(\eta_{REC})(\eta_{TS})(\eta_{SGS/EPGS})\Delta Clean \quad \text{[Equation 3.1.4]}$$

Energy lost due to lower field efficiency than predicted:

$$E_{LOSS,FIELD} = (E_{AVAIL})(\%AreaTracking)(Clean)(\eta_{REC})(\eta_{TS})(\eta_{SGS/EPGS})\Delta\eta_{FIELD} \quad \text{[Equation 3.1.5]}$$

Energy lost due to lower receiver efficiency than predicted:

$$E_{LOSS,REC} = (E_{AVAIL})(\%AreaTracking)(Clean)(\eta_{FIELD})(\eta_{TS})(\eta_{SGS/EPGS})\Delta\eta_{REC} \quad \text{[Equation 3.1.6]}$$

Energy lost due to greater heat losses from the storage tanks and thermal transport piping than predicted:

$$E_{LOSS,TS} = (E_{AVAIL})(\%AreaTracking)(Clean)(\eta_{FIELD})(\eta_{REC})(\eta_{SGS/EPGS})\Delta\eta_{TS} \quad \text{[Equation 3.1.7]}$$

Energy lost due to lower SGS and EPGS thermal efficiency than predicted:

$$E_{LOSS,SGS/EPGS} = (E_{AVAIL})(\%AreaTracking)(Clean)(\eta_{FIELD})(\eta_{REC})(\eta_{TS})\Delta\eta_{SGS/EPGS} \quad \text{[Equation 3.1.8]}$$

The change in the efficiency factor is determined by the predicted values being chosen as the reference case. For example, Equation 3.1.8 would be computed as:

$$[(E_{AVAIL})(\%AreaTracking)(Clean)(\eta_{FIELD})(\eta_{REC})(\eta_{TS})]_{PRED}*(\eta_{SGS/EPGS,PRED} - \eta_{SGS/EPGS,ACT}) \quad \text{[Equation 3.1.9]}$$

where the subscripts PRED and ACT indicate predicted and actual terms, respectively.

The sum of the loss estimates in Equations 3.1.3 through 3.1.8 is not equal to the total lost electricity. This is because the loss expressions assume discrete difference. Because the same reference (predicted) is used in these equations, they do give the relative contribution of each loss factor, so the actual losses can be quantified. To apportion that part of the lost electricity not accounted in the partial differential equations, all loss factors are multiplied by the correction factor in Equation 3.1.10.

$$F_{CORR} = \frac{E_{GROSS,PRED} - E_{GROSS,ACT}}{E_{LOSS,UNAVAIL} + E_{LOSS,\%TRACK} + E_{LOSS,CLEAN} + E_{LOSS,FIELD} + E_{LOSS,REC} + E_{LOSS,TS} + E_{LOSS,SGS/EPGS}} \quad \text{[Equation 3.1.10]}$$

The equations and energy flow diagram in this section were originally documented in a July 15,1998, memo by S. Faas.[3]

It is important to note that $E_{UNAVAIL}$ in Figure 19 goes through the same loss analysis that E_{AVAIL} does. This method of loss attribution was used rather than attributing all generation losses during these times to plant availability losses because it more accurately categorizes losses. The lost electricity analysis serves as a tool for plant optimization, and this method of dealing with $E_{UNAVAIL}$ provides a more accurate picture of the electricity that would be gained if a specific problem were corrected. Using this method, the electricity loss attributed to plant availability is the actual amount that would be gained if the plant availability were at the design level. Correcting the availability problems would not, however, influence the plant's performance in areas such as the percent area of the field area tracking, and receiver efficiency.

3.1.2.2. Model Validation

In validating the SOLERGY model for Solar Two, to the extent possible, actual plant conditions were incorporated into the model as opposed to design plant conditions. At a minimum, this included actual heliostat availability (daily average) and cleanliness.

The areas chosen for model validation were:

- Energy to the working fluid
- Thermal losses between the receiver and the SGS
- Operating efficiency of the SGS/EPGS
- Electric parasitic consumption.

The SOLERGY validation for Solar Two is still in its early stages; we are currently working on validation of energy to the working fluid. The results of the SOLERGY validation will be included in the Final Project Report.

3.1.3 Results

3.1.3.1. Lost Electricity Analysis

The results of the lost-electricity analysis are summarized in monthly plots. Figure 20 and Figure 21 show examples of two of these plots for September 1998. Figure 20 shows a pie chart that quantifies the gross electricity lost due to various causes. This plot quantifies each loss fraction in terms of electrical energy. The whole pie represents the difference between the total SOLERGY predicted gross generation and the actual Solar Two generation. The individual pie wedges quantify the fraction of loss attributed to each loss factor. This plot also explicitly calls out the availability losses. These availability losses are operator discretion, weather, tube thaw/receiver warm-up, receiver availability, and miscellaneous availabilities.

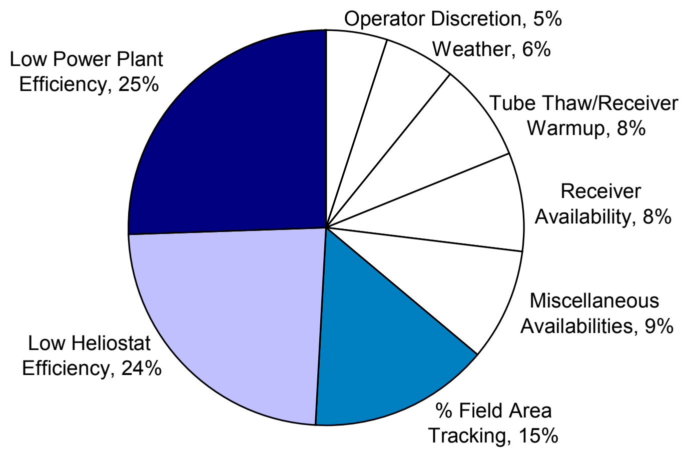

Figure 20. September 1998 Solar Two Gross Electricity Loss Contributions

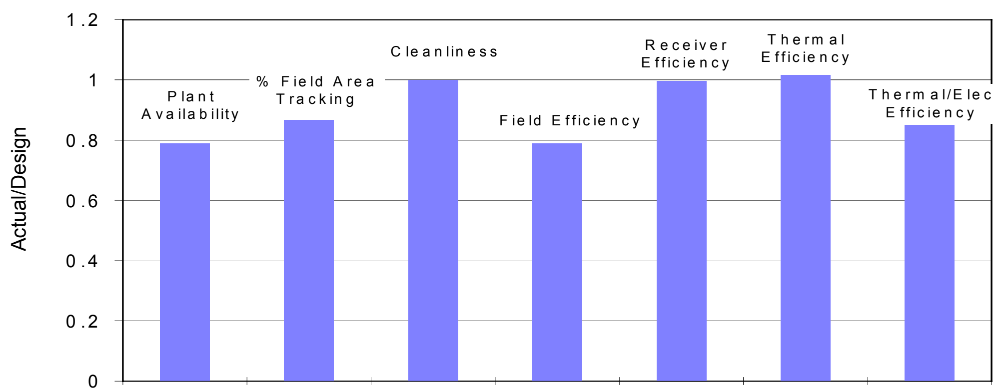

Figure 21. September 1998 Solar Two Plant system Effectiveness

Figure 21 shows an "effectiveness" chart that corresponds to the energy flow diagram shown in Figure 19. Each bar in Figure 21 is a ratio of the Solar Two system efficiency to the SOLERGY system efficiency. A bar with a value of one represents a Solar Two system that met predicted performance; any value less than one represents performance below the predicted level. Figure 21 illustrates that the September 1998 plant availability was approximately 80 percent of design availability, which was 90 percent. It also shows that the field cleanliness, the receiver efficiency, and thermal efficiency were at design level, whereas the percentage of the field tracking, field efficiency, and the thermal-to-electric conversion efficiency were below design level. It should be noted that the thermal to electric conversion efficiency losses were more significant than usual in September because of a test that was run to characterize the SGS. The losses illustrated in this plot are consistent with those in Figure 20.

3.1.3.2. Model Validation

There is still uncertainty in several areas of the data and modeling. The two potentially most significant uncertainties are the SGS flow meter readings and the heliostat tracking accuracy, particularly in windy conditions. It was suspected that the SGS flow meter readings were higher than the actual flow rate or that the actual field efficiency was at times lower than that calculated under non-windy test conditions. The plot in Figure 22 illustrates the effect on the loss distribution if each of these factors were reduced 10 percent. The difference in the modified bar heights from the baseline bar height can be treated as a preliminary uncertainty band.

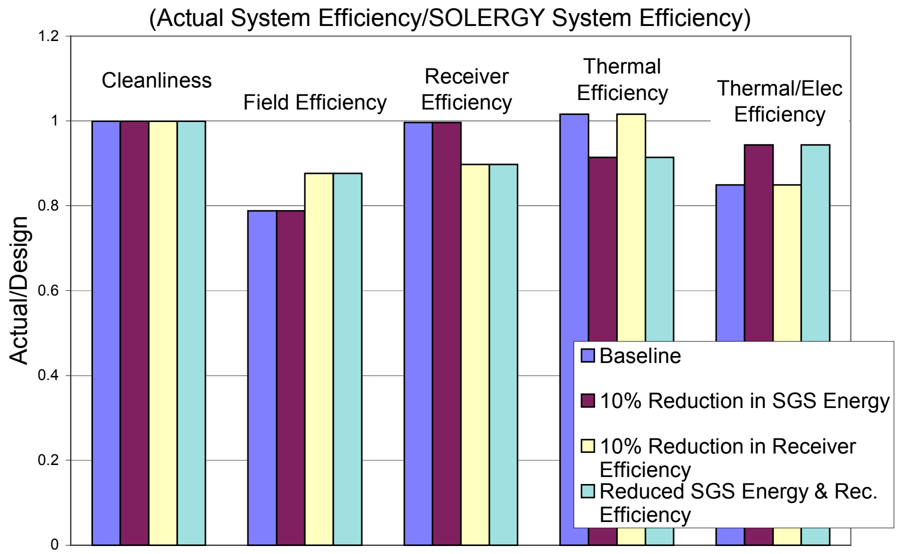

Figure 22. September 1998 Sensitivity of System Effectiveness

Preliminary results show that during ideal weather conditions (i.e., no wind or high, thin clouds), SOLERGY does a fairly good job of predicting energy collected by the working fluid. in Figure 23 shows an example of the plot of power to the working fluid for September 30, 1998. This was a day that had morning clouds that cleared abruptly and ideal weather once the clouds cleared. During the time SOLERGY determined the receiver should be collecting energy for this day, the results show 6.5 percent error between Solar Two and SOLERGY. (Notice that Solar Two actually “beat” SOLERGY at the end of the day. This is because the operators tracked the sun into the ground.) This margin of error is indicative of days with no equipment or weather problems.

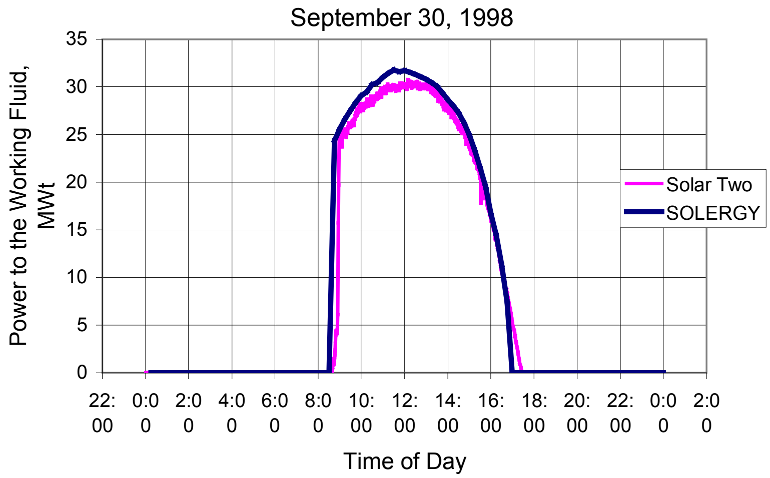

Figure 23. Actual and Predicted Power to the Working Fluid, September 30, 1998

On windy days, however, this analysis pointed out discrepancies that need further investigation. Figure 24 plots power to the working fluid, with an example of a discrepancy for September 29, 1998. (It should be noted that the Solar Two plant was shut down early on September 29th for reasons unrelated to the weather.) The difference between the modeled collections and the actual is greater than 20 percent. The SOLERGY wind loss model (based on a study conducted by Siebers and Kraabel[4]) is based solely on receiver surface area, but it was suspected that during even slightly windy conditions there may be significant thermal losses from the receiver. Receiver efficiency tests in high winds have recently been completed, and the receiver efficiency was determined to be essentially as predicted. As a result of additional testing, it has been determined that the higher than predicted losses can be attributed to heliostat tracking errors in high wind (higher spillage).

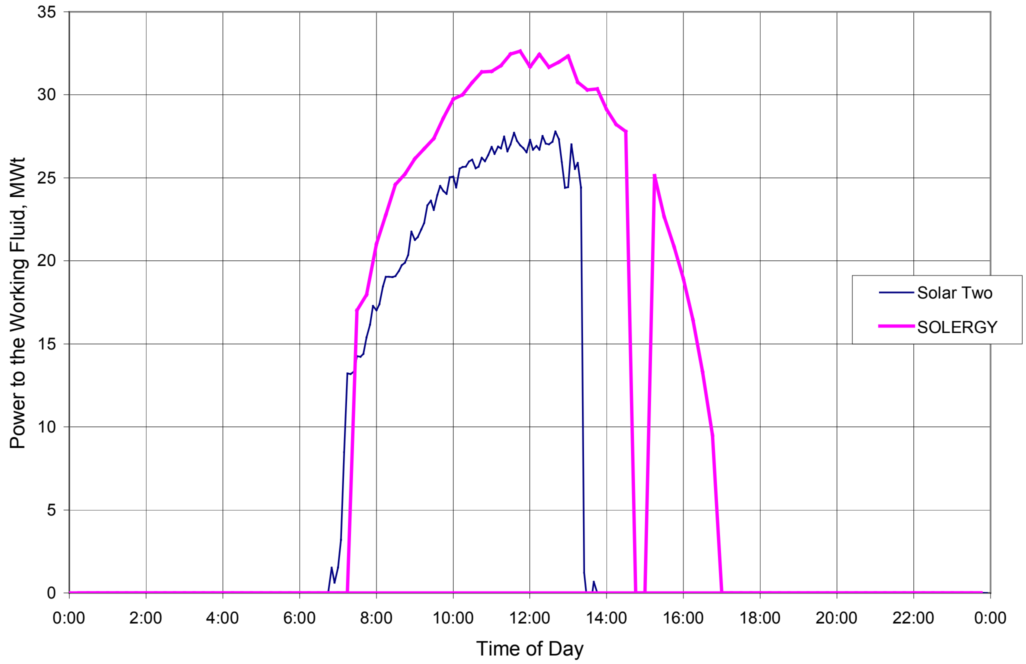

Figure 24. Actual and Predicted Power to Working Fluid, Windy Conditions, September 29, 1998

3.1.4 Conclusions and Recommendations

The Solar Two performance evaluation activity had reached the point where it was able to help with the plant optimization objectives. The plant, however, never achieved operation at design performance or full production. The reasons for this were:

- The plant performance is based on its first and only year of operation
- Design problems needed to be resolved which contributed to the plants low availability and low power production
- The old hardware in the heliostat field was not reliable, reducing heliostat availability and thermal collection
- The O&M personnel were learning plant operation throughout the course of the project and, therefore, operating procedures were not yet optimized.

On days when the plant was allowed to operate all day, however, plant data agreed well with SOLERGY predictions, and agreed nearly perfectly when a field degradation factor of 10 percent was assumed. This confirms that SOLERGY can be used to accurately model the performance of power towers running in a mature operating state.

Model validation is critical to understanding what contributes to low production and to implement improvements to the plant. To refine the loss insolation and performance optimization process, model validation must be completed. The biggest challenge in model validation is better characterizing the heliostat field conditions and the heliostat tracking errors. Analysis also must be extended to include the electric parasitic consumption.

In furtherance of these goals, the T&E Team undertook an additional evaluation task, heliostat tracking error. Heliostat tracking errors are believed to be significant contributors to the deficiency in energy collection. The initial results of the heliostat tracking error evaluation are discussed in the following.

4.0 Heliostat Tracking Error

4.1 Analysis of Solar Two Heliostat Tracking Errors

4.1.1 Objectives

The objective of this study was to explore the geometrical errors that reduce heliostat tracking accuracy at Solar Two. The basic heliostat control architecture is described. Then, the three dominant error sources are described and their effect on heliostat tracking is visually illustrated. The strategies currently used to minimize, but not truly correct, these error sources are also shown. Finally, a novel approach to minimizing error is presented.

The heliostat field consists of 1818 heliostats that were developed by Martin Marietta Co. (MMC) during the early 1980's for the Solar One project and 108 Lugo heliostats that were added to the field for the Solar Two project. Kelly and Singh[5] described the design of the Solar Two plant and the changes from Solar One. The design specifications for Solar One heliostats required root-mean-square (RMS) tracking accuracy of less than 1.5 milliradians (mrad) in no-wind conditions for each horizontal and vertical axis (2.1 mrad total for both axes). The molten salt receiver at Solar Two has 1/3 the surface area of the water/steam receiver used at Solar One, increasing the potential for spillage – light reflected from heliostats that misses the receiver.

The project goals at Solar Two have been oriented more toward proving operation of the molten salt system than characterizing the heliostat field, since the heliostat field was proven during Solar One. Some changes to the field were made, however, to better match the new receiver. To increase the field area and redistribute the flux profile, salvaged mirror modules were used to replace the most corroded mirror modules and to build the Lugo heliostats. These cost-saving compromises resulted in a reduction in the optical beam quality of the heliostats. Re-alignment of the heliostats for the smaller receiver also introduced errors to the field. Jones et al[6] provided more details on the Solar Two heliostat field optics.

The Solar Two plant has recently met thermal to electric conversion and parasitic power use goals. The energy collection, however, has been 10 to 20 percent lower than expected, suggesting that the heliostat field was not performing up to expectations. The accuracy of heliostat tracking was believed to be a possible cause of the reduced performance. The observation of occasional miss-tracking heliostats and excessive flux on the oven covers (the white panels located directly above and below the receiver) bolstered this suspicion. A study was initiated to investigate the possible causes of poor heliostat tracking. In addition to hardware failures, it was found that a number of geometrical error sources could interfere with proper heliostat tracking.

4.1.2 Methods

One portion of the Solar Two heliostat tracking control system controls the original Solar One field. It is an open loop distributed system with the purpose of aiming heliostats so that the reflected beam will be continuously incident on the desired receiver aim point as the sun moves. There are three hardware components in the control system[7]. The 1818 heliostat controllers (HC) calculate the required azimuth and elevation angles given the sun position and aim point and move the heliostats to those angles. The 64 heliostat field controllers (HFC) handle communications with the maximum of 32 heliostats under their control. The third component is the heliostat array controller (HAC) that interfaces with the operator, calculates the sun position vector and aim points, and communicates with the HFC units. Because of the high cost of replacing the heliostat control system, the basic Solar One control system was used at Solar Two. The HAC computing hardware was replaced but most of the Solar One HAC software was transferred. The 108 new Lugo heliostats use a slightly different control system that was interfaced with the original system. The analysis of this system has not been completed. Since the time Solar One tracking algorithms were developed and implemented, new techniques have been developed that can improve heliostat tracking accuracy. Unfortunately, the distribution of the tracking control logical functions among the different controllers is believed typically to make it difficult and costly to implement these techniques.

4.1.2.1. Tracking Error Sources

This heliostat control system is subject to many different types of error sources. Some of the most common error sources are azimuth rotational axis tilt, incremental encoder granularity, control system granularity, atmospheric refraction, gravity bending, pivot point offset, mirror alignment or "canting" non-orthogonality relative to the heliostat centerline, and azimuth and elevation reference position (referred to as the mark position) error. Other errors, which probably contribute a small amount to the tracking error, are sun position algorithms, latitude and longitude field variation, leap second, computation time error, transmission time error, and algorithm accuracy.

A geometrical error model was developed that predicts the tracking error of a single heliostat over the course of a single day based on information about its various geometrical error sources. Stone[8] described the error model geometry and mathematics in more detail. The error model was implemented in a spreadsheet to produce the results and plots shown here. Three geometrical error sources are believed to be dominant at Solar Two and are the focus of this report:

- Azimuth rotational axis tilt
- Mirror alignment/canting non-orthogonality errors
- Encoder reference position error.

In addition, the effect of the procedure currently used at Solar Two to minimize these geometrical errors is shown. A novel approach to improving heliostat tracking is also presented. The purpose is to:

- Familiarize the reader with the geometrical error sources present at Solar Two.
- Show that the approaches used to address these errors at Solar One, at Solar Two, and the new approach presented in this report are merely "Band-Aids" aimed at minimizing the problem, not true fixes that correct the problems.

To objectively evaluate strategies to improve heliostat tracking, one must base decisions on more information than how the strategy affects a single heliostat on a single day, as shown here. Ideally, the strategies would be compared based upon their effect on the tracking of the entire field of heliostats on an annual basis. This is addressed in a subsequent section of this report.

Azimuth Axis Tilt Errors

At the time the heliostat field was installed, the azimuth rotational axis tilt was the primary error source considered in the design of the system. This type of error would most likely occur due to a tilt of the heliostat pedestal, so is often referred to as pedestal tilt error. It can also occur due to other mechanical errors that tilt the azimuth rotational axis relative to the vertical coordinate at the plant, such as errors in the gear drive. At Solar One, a very accurate, electronic inclinometer was used to measure the azimuth axis tilt angle and the foundation bolts at the base of the pedestal were adjusted to minimize this error. This was an expensive procedure, and it still did not totally eliminate the error. A survey of 16 randomly selected heliostats at Solar Two indicated the average tilt magnitude was about 0.5 mrad[6].

Figure 25 shows the horizontal and vertical tracking errors on summer solstice of a heliostat 1,000 feet (ft.) north of the tower with a 1 mrad pedestal tilt in the north direction. The target sits atop the tower at a height of 296 ft., matching the location of the receiver midpoint at Solar Two. Each point on the graph corresponds to the centroid location of the heliostat beam on the target at 1-hour increments of local solar time. Three of the data points have a label identifying the solar hour (6, 12, and 18) to indicate the direction of the beam movement from morning to afternoon. Additionally, there is substantial data regarding the graph in the adjacent boxes. The heliostat location and date are listed above the chart. The error profile used in the calculations is listed to the top right. In this case, there is only a north-south pedestal tilt of +1 mrad (north). In addition to the graph that shows the movement of the beam (its "signature"), the box to the lower right contains data on the tracking accuracy of the heliostat. The daily RMS errors are followed by the daily peak tracking errors. Both metrics are tallied for each axis and also for the total of the two axes.

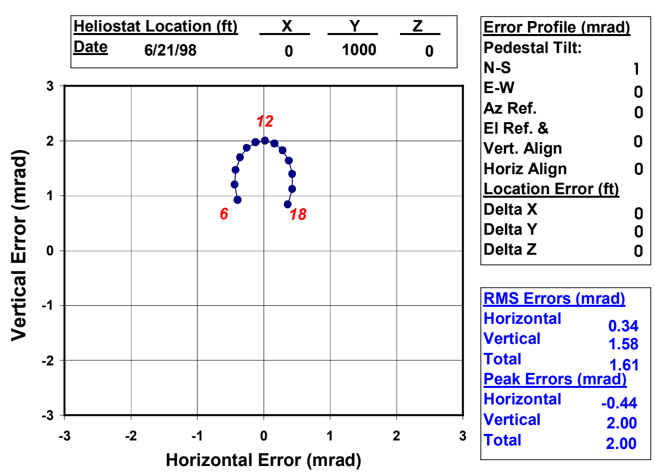

Figure 25. Tracking Error Signature on Summer Solstice of a North Field Heliostat With a 1-mrad Pedestal Tilt to the North

At noon, when the tower and the sun are due south of the heliostat, the northward pedestal tilt causes the beam to track high on the target. Conversely, a pedestal tilt to the south would cause the beam to track low at solar noon. In the morning and afternoon, the sun is not due south of the heliostat, causing the tracking error to have both vertical and horizontal components. As can be seen, the 1-mrad pedestal tilt has caused a peak 2-mrad beam position error because of the law of reflections. The daily RMS beam tracking error is a substantial 1.61 mrad. Tracking errors scale linearly with error sources, so a 2 mrad northward tilt would lead to a peak error of 4 mrad and a daily RMS error of 3.22 mrad for this heliostat.

Figure 26 another example of pedestal tilt. In this case, the pedestal is instead tilted 1 mrad in the east direction. The movement of the beam over the day has changed substantially, and the daily peak and RMS tracking errors have dropped slightly to 1.23 and 1.26 mrad respectively. The location of the heliostat in the field also affects the nature of the tracking errors. If the heliostat shown in Figure 26 were moved to 800 ft. east of the tower, it would have the tracking signature shown in Figure 27. This heliostat has a peak beam error of 2 mrad and a daily RMS tracking error of 1.96 mrad. Heliostats in the south field tend to have tracking signatures similar to those in the north field for equivalent error profiles. The same is true of east and west field heliostats. Figure 27 shows a heliostat 400 ft. south and west of the tower with a 1-mrad pedestal tilt in the southeast direction. It is difficult to visualize how the error source causes the beam movement of this heliostat that nonetheless has similar daily peak and RMS tracking errors of 2.00 and 1.81 mrad respectively.

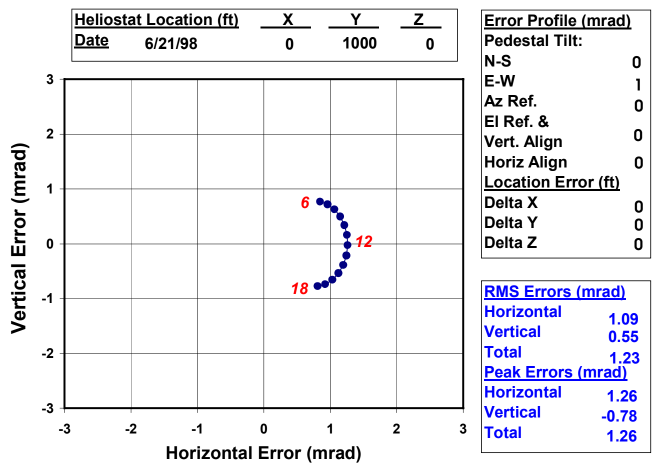

Figure 26. Same as Figure 25, But Pedestal Tilt is to the East

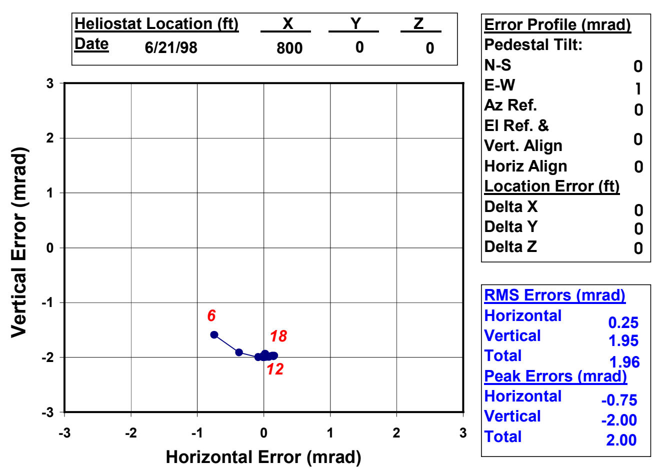

Figure 27. Same as Figure 26, But Heliostat East of the Tower

Seasonal effects can also be seen in the tracking errors. One would expect larger changes for heliostats in east, west, and southern region of the field since the tracking angles of these heliostats change more with season than the heliostats in the northern region of the field. Figure 29 shows the same scenario as Figure 28, except on winter solstice instead of summer solstice. The signature has changed (note the starting and ending points), yet the peak and daily RMS tracking accuracy remain similar.

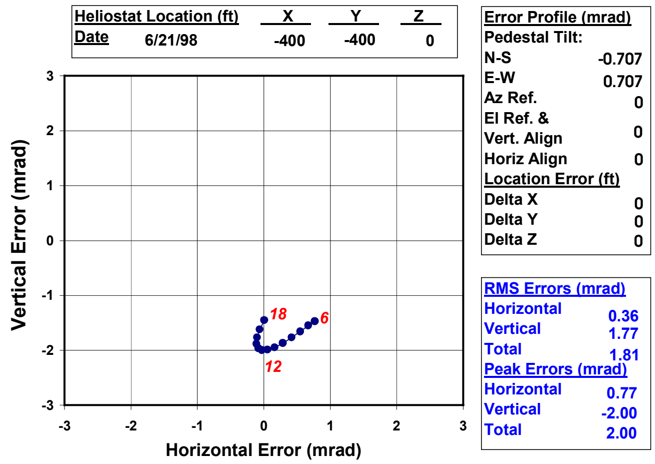

Figure 28. Tracking Errors on Summer Solstice of a Southwest Heliostat With 1 mrad of Pedestal Tilt in the Southeast Direction

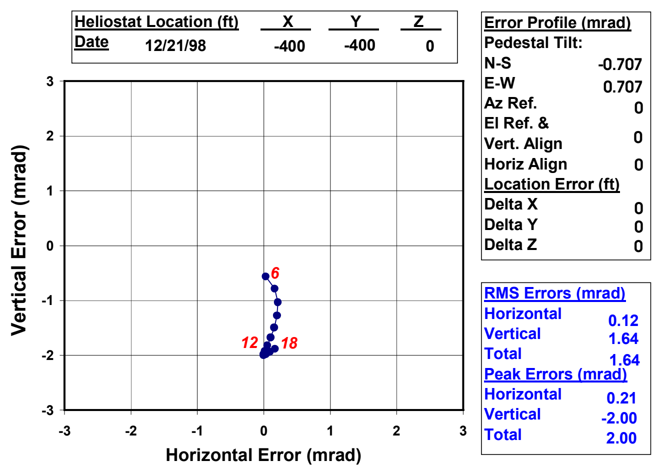

Figure 29. Same as Figure 28, But on Winter Solstice

Mirror Alignment/Canting Errors

At Solar One, all the heliostats were aligned, or "canted" for a 1,200-foot focal length. This caused the beams of heliostats close to the receiver to be quite large. In fact, spots from all 12 facets could be seen rather than one contiguous beam. This worked well for the large Solar One receiver with low flux limits. To minimize spillage on the smaller, Solar Two receiver, the heliostats were re-aligned to shorter focal lengths. A study showed that aligning the inner 17 rows of heliostats to their slant range (the line-of-sight distance to the receiver) would provide as much benefit as re-canting the entire field, so this was done[6]. Unfortunately, a tracking error source may have unintentionally been increased in the process of mirror alignment.

A tracking error occurs when the heliostat mirrors are aligned to a point that does not lie on the normal vector to the heliostat's local elevation plane defined by the gear drive assembly. In this case, the alignment is non-orthogonal to the local elevation plane. This can easily occur in both optical (on-sun and lookback) alignment techniques as well as mechanical approaches (inclinometer and offset measurement). The error source can be divided into two components, vertical and horizontal. The vertical component is indistinguishable from an elevation reference mark error.

Figure 30 shows a heliostat 800 ft. west of the tower with a 1-mrad horizontal alignment error. This heliostat has a daily peak tracking error of 2 mrad and a daily RMS tracking error of 1.88 mrad. The tracking signature is unique in the large shift that occurs from 17 to 18 hours solar time. This is the result of singularity, when the heliostat azimuth axis must rotate quickly to properly track the sun. This occurs when a heliostat is pointing nearly face up and is in line between the sun and the tower. Figure 31 represents the interesting fact that the change in sun trajectory encountered just 1 month later prevents this singularity from occurring. Stone and Lopez[7] have shown how the biasing approach can in some cases double tracking errors when used on heliostats in the south field that undergo singularity.

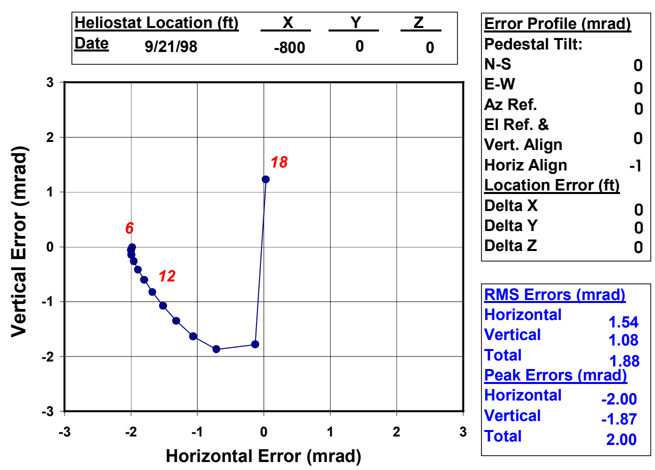

Figure 30. Tracking Error Signature on the Autumnal Equinox of a West Field Heliostat With a Horizontal Alignment Error of 1 mrad

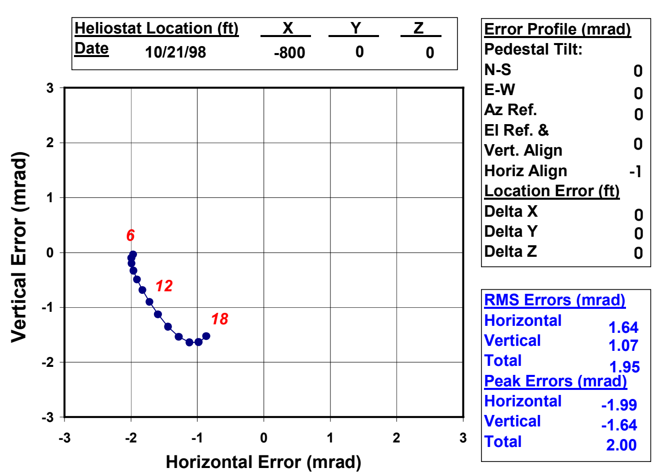

Figure 31. Same as Figure 30, But 1 Month Later When Singularity No Longer Occurs

Encoder Reference Errors

The function of the heliostat control system is to rotate the heliostat to azimuth and elevation angles that will result in the reflected beam being incident at a given aim point. An encoder is used to determine when the heliostat is at the required angles. The accuracy of this process depends both upon the accuracy of the encoder itself, and also upon the accuracy of a reference that correlates the encoder position to the plant coordinate system. The MMC heliostats at Solar Two use incremental, optical encoders with a built in "mark" pulse to establish the references. (The Lugo heliostats use incremental, hall-effect encoders, while the limit switches establish the reference positions.) When the incremental encoders are first installed on the heliostat, the reference mark is positioned within 1 degree of the desired location. This position, however, should ideally be established to within a fraction of a milliradian (one to two orders of magnitude more accurate).

Many believe that an error in the encoder reference position introduces a constant shift in the heliostat beam tracking location. This is false. Figure 32 shows the effect of a 1-mrad elevation reference position error on a north heliostat. The reference error causes a time-variant tracking error similar to that caused by pedestal tilt (Figure 25). Likewise, Figure 33 shows a time-variant error for an east field heliostat with an azimuth reference position error. Figure 26 shows that in this case, the tracking error signature is different from that for the same heliostat with 1 mrad pedestal tilt. However, the daily RMS error is nearly the same (1.22 mrad versus 1.23 mrad). The day of the year and field location seem to have a larger impact on the daily RMS tracking error than the particular error profile. Of course, the magnitude of the tracking error scales linearly with the magnitude of the error sources. All the error profiles explored so far have totaled 1 mrad.

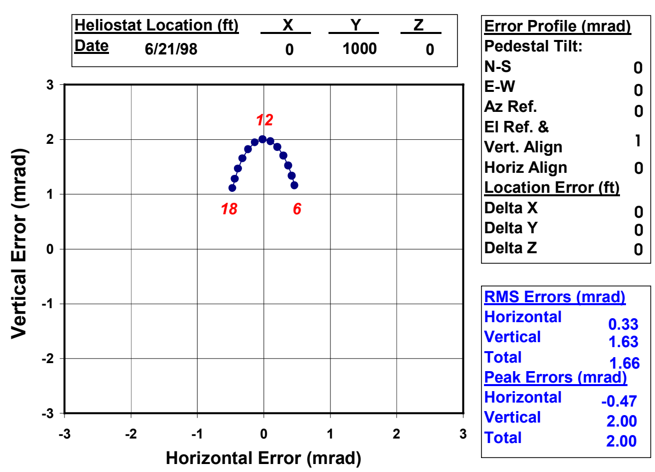

Figure 32. Tracking Errors for a North Field Heliostat on Summer Solstice Due to a 1 mrad Elevation Reference Position Error

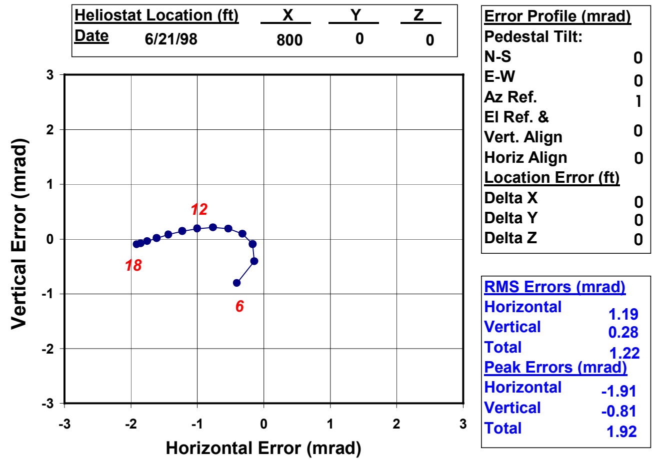

Figure 33. Tracking Error Signature for an East Field Heliostat on Summer Solstice With a 1 mrad Azimuth Reference Position Error

The encoder reference positions are typically found by tracking the heliostat beam on a far-away target, thus permitting a high accuracy in the measurement. However, since heliostats typically have errors such as pedestal tilt and canting non-orthogonality, these errors propagate through and lead to errors in the encoder reference position measurement. The addition of encoder reference position error changes the tracking signature of the heliostat, with the intent of improving it.

4.1.2.2. Mark Position Adjustment or "Biasing"

At Solar One and at Solar Two, heliostat tracking accuracy has been improved by adjusting the encoder reference position errors. This is called heliostat biasing because the location of the encoder reference position (the mark position) of every heliostat is stored as a "bias" value in a database. The Beam Characterization System (BCS) is used to measure heliostat tracking errors needed to perform biasing. Mavis[9], King[10], and Strachan[11] described the BCS. Basically, a camera records an image of the heliostat beam on one of the four targets located beneath the receiver. Normally, the centroid of the recorded image provides the tracking location of the beam.

Biasing is a Band-Aid approach aimed at minimizing daily tracking errors, but does not truly correct the problem. Another problem with biasing heliostats is that changing the bias values does not introduce a constant shift in the beam. Rather, a time-variant tracking error is introduced, as was shown earlier. Biasing uses one time-variant tracking error source to compensate for others. Sometimes, this is very effective. Other times it is not.

Two of the key parameters in heliostat biasing are the number of BCS measurements per day used to adjust the bias, and the number of updates performed per year. The subsequent section of this report explores the relative merits of the many potential combinations of these parameters by running hundreds of case studies. Only two scenarios will be shown here to illustrate the impact of biasing.

To start, a heliostat with a simple error profile, consisting of a single error source, was investigated. Figure 34 shows the same scenario as Figure 25, except the elevation bias has been adjusted (note the elevation reference error of –1 mrad) so as to minimize the heliostat tracking error at noon. The peak tracking error has been reduced from 2.0 to 0.89 mrad and the daily RMS error has been reduced from 1.61 to 0.67 mrad. This is a significant improvement, although time-variant tracking errors still exist. However, noon was the best time to bias this heliostat. Had biasing instead been performed at 10 or 14 hours, the RMS tracking error would increase to 0.86 mrad, while the peak error would rise to 1.43 mrad. If three tracking error measurements at 10, 12, and 14 hours had been used to bias the heliostat, an improvement very similar to the noon bias would occur.

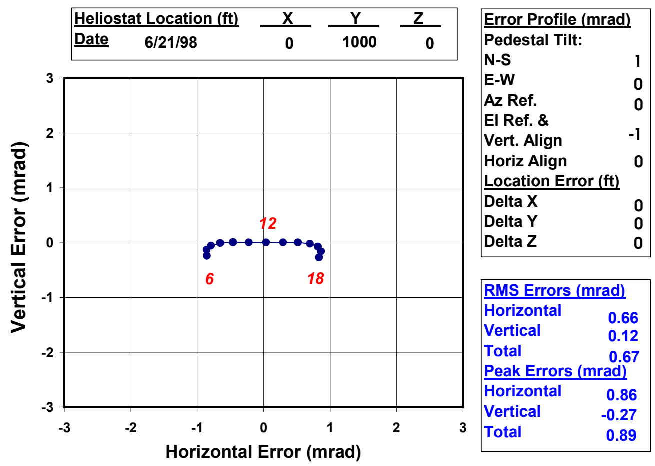

Figure 34. Figure 25 Heliostat Biased at Noon With a –1 mrad Elevation Reference Position Error

The second scenario involves a more likely error profile for a heliostat in the southeast region of the field. This heliostat had 1 mrad of pedestal tilt in the northwest direction and 1 mrad of alignment error equally distributed between horizontal and vertical axes. Finally, this heliostat had an azimuth bias error of 1 mrad. Figure 35 shows the tracking signature of this hypothetical heliostat. Figure 36 shows the tracking signature for this heliostat after biasing using a tracking error measurement at solar noon. The signature has been changed because of the influence of the encoder reference error that was introduced in biasing. Table 17 lists the impact of biasing the heliostat at different times and using multiple tracking error measurements. As with the previous scenario, Table 17 indicates that one measurement is capable of delivering results almost as good as that achieved with multiple measurements if the timing is optimal (slightly before or after solar noon).

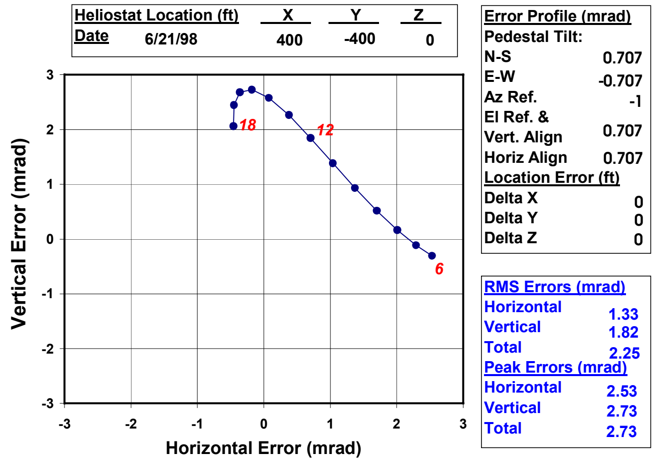

Figure 35. Tracking Error Signature of a Southeast Field Heliostat on SS With a 1 mrad Pedestal Tilt to the Northwest and 1 mrad of Total Horizontal and Vertical Alignment Error

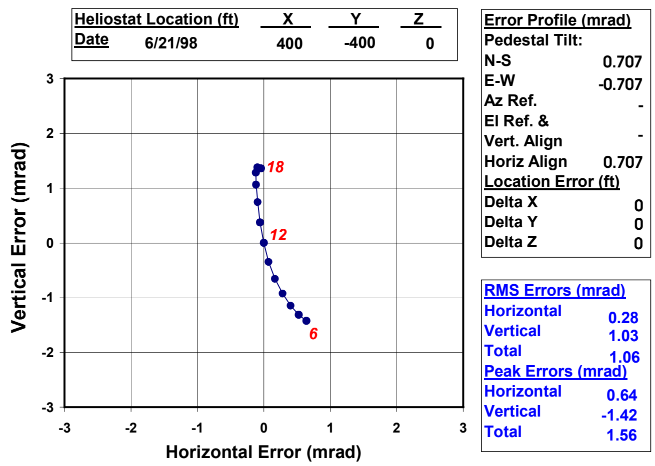

Figure 36. Heliostat from Figure 35 After Biasing at Noon

Table 17. Results of Variations in Biasing for the Hypothetical Heliostat Shown in Figure 35

Tracking Error Measurement Times (solar hour)	Daily RMS Tracking Error (mrad)	Daily Peak Tracking Error (mrad)
12	1.06	1.56
14	1.30	2.04
10,12,14	0.96	1.38
12,14,16	1.10	1.73

At Solar One, a bias adjustment strategy using three tracking error measurements over the day was used[9]. Additionally, the BCS was automated to help take large numbers of measurements. The automation of this system was complicated and it experienced conflicts with the master control system that initially limited its use. For these reasons, a simple, PC-based system was installed at Solar Two and a biasing approach using only one BCS measurement per day was selected to encourage high quality over high quantity in the BCS measurements performed. It was also believed that if the one BCS measurement needed in this approach was performed (optimizing tracking accuracy) at a time of day when that heliostat was likely to deliver the most power to the receiver, the integrated daily energy delivered to the receiver would also be maximized. For this reason, time guidelines were set for biasing each quadrant of the field based upon when the combined solar insolation and cosine performance were maximal. The guidelines called for the west field to be biased just before solar noon, the east field just after solar noon, and the north and south fields about solar noon.

4.1.2.3. Approach to the Move Strategy

If there is an error in the known location of a heliostat, a tracking error will result. Figure 37 shows a heliostat 1,000 ft. north of the tower with a 1-ft. shift east and up from its true location, but no other error sources. The heliostat beam likewise shifted 1 ft. east and up on the target. Figure 37 shows the angular values of the shift rather than the linear values. The slant range of the heliostat, 1040 ft. in this case, relates these two measures. The locations of the heliostats at Solar Two were surveyed very accurately (to a few centimeters accuracy, most likely) and are stored in a database, so tracking errors of this type are likely negligible.

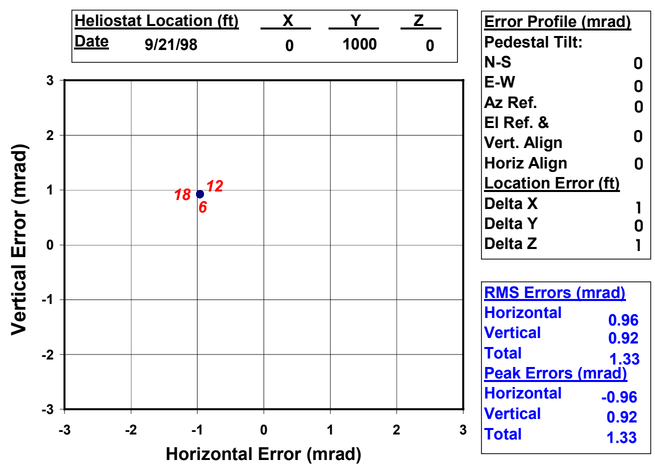

Figure 37. Tracking Error Signature of a Heliostat With Location Errors of 1 ft. Up and East

This error source offers a possible method for improving the daily heliostat tracking accuracy that has never before been proposed. The beam is simply shifted, providing a potentially desirable advantage over biasing. This approach to improving heliostat tracking will be termed the "move" strategy. Its effect will be shown in the same scenarios explored in the bias strategy.

Figure 38 shows the impact of the move strategy on the simple error profile of the heliostat shown in Figure 25. Unlike the bias approach, the move strategy is more effective at 10 and 14 hours than at noon. In this "best" case, the RMS error is comparable to the bias strategy, although the peak error is 0.3 mrad larger. In the worst cases, the move strategy has a small advantage of 0.2 mrad only in the peak error. Using measurements at 10, 12, and 14 hours, the move strategy peak tracking error is again 0.3 mrad larger than the bias strategy. Like the bias strategy, a single measurement approach is nearly as good as a three-measurement approach.

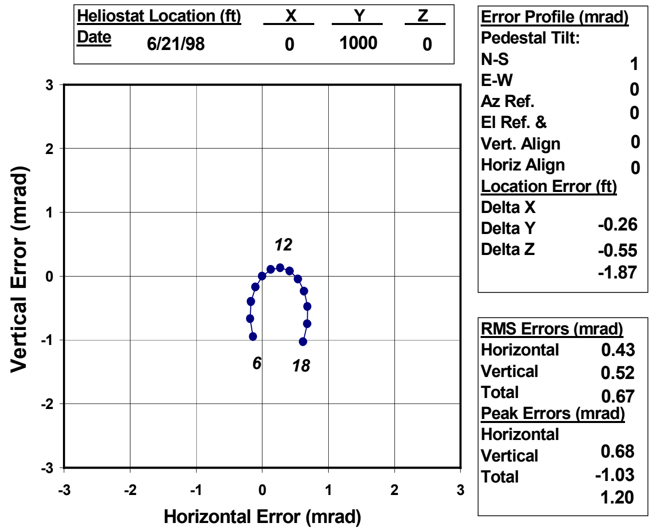

Figure 38. Heliostat from Figure 25 Corrected With the Move Strategy at 10 Hours Solar Time

Figure 35 shows the uncorrected tracking signature for the second scenario. Figure 39 shows the impact of the move strategy performed with a single tracking error measurement from solar noon. As expected, the beam path has simply been shifted. Table 18 shows the impact of measurement time and multiple measurements on the move strategy results. For this particular heliostat, the bias strategy provided better results than the move strategy, because the encoder reference position errors introduced in biasing actually helped minimize the amount of beam drift over the day caused by the other error sources. The opposite could occur for another heliostat, with biasing increasing the beam drift and providing worse RMS tracking accuracy than the move strategy. So it is unclear which strategy is superior.

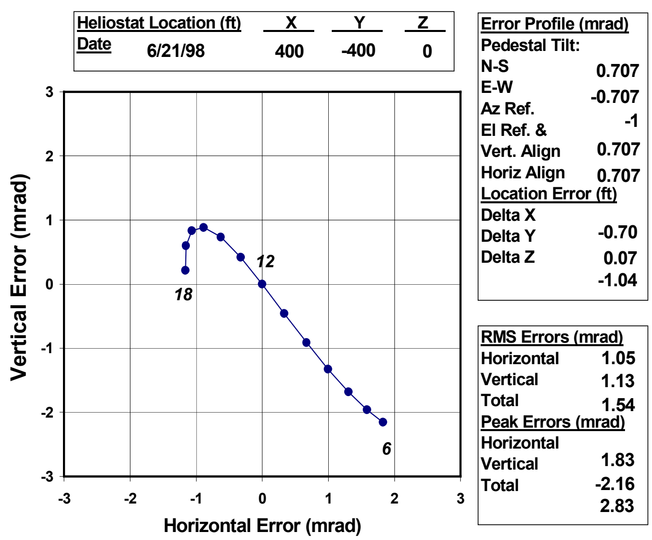

Figure 39. Heliostat From Figure 35 Corrected With the Move Strategy at Solar Noon

Table 18. Results of Variations in the Move Strategy for Hypothetical Heliostat Shown in Figure 35

Tracking Error Measurement Times (solar hour)	Daily RMS Tracking Error (mrad)	Daily Peak Tracking Error (mrad)
12	1.54	2.83
14	2.00	3.79
10, 12, 14	1.53	2.77
12, 14, 16	1.87	3.59

4.1.3 Results

Pedestal tilt error was introduced when the heliostat is installed. Alignment or "canting" non-orthogonality error was probably inadvertently made much worse at Solar Two when the inner 17 rows were re-canted. Encoder reference position or bias error occurs during initial installation or subsequent replacement. It is currently also used to try to minimize the other error sources in a process called biasing. An error in the heliostat location can also cause tracking errors. Although this is not a likely error source at Solar Two, it is another potential Band-Aid solution to minimize other errors and has the advantage of introducing a constant shift in the beam position. It is unclear whether biasing or moving is a better strategy. Likewise, it is unknown how many tracking error measurements used in either process will deliver the best cost-to-results ratio. These questions are addressed in Section 4.2 of this report, which investigates the effect of different strategies to improve tracking by estimating their effect on annual performance of the entire field.

It was shown that the tracking error signature (the path of the heliostat beam) can vary significantly depending upon the error source profile, the location of the heliostat, and the day of the year. However, the variation in the uncorrected daily RMS tracking error was comparatively less (1.22 to 1.96 mrad) for the scenarios with a 1 mrad total error profile. In fact, there are many possible combinations of error profiles that could yield the same daily RMS beam tracking error. This fact is used in the companion paper.

An error-correcting model can also be used to greatly improve tracking. Stone[8] has shown this can provide tracking accuracy of 0.5 mrad RMS or better. This appears to be the clear choice for the approach to use at future plants. In the past, it was thought that implementing such an error-correcting approach at Solar Two was difficult and would require replacing expensive hardware. It is likely, however, that a novel approach using only software modifications could be developed and implemented in 6 months time. This would solve the time-variant tracking errors currently affecting the project.

4.2 Analysis of Strategies to Improve Heliostat Tracking at Solar Two

4.2.1 Objectives

The objective of this analysis is to investigate different strategies that can be used to improve the tracking accuracy of heliostats at Solar Two. To accomplish this task, an attempt was made to evaluate strategies on the basis of how they would affect the entire field over the course of a year, rather than a single heliostat on a single day. The different strategies were analyzed using a geometrical error model to determine their performance over the course of a day. By using the performance of heliostats in representative locations of the field and on representative days of the year, an estimate of the annual performance of each strategy is presented. The background for this section is presented in Section 4.1. The Lugo heliostats are not included in this study.

4.2.2 Methods

4.2.2.1. Strategies to Improve Tracking Accuracy

Three strategies for improving heliostat tracking are discussed in the following.

- **Mark Position Adjust or "Biasing"** – Use of tracking accuracy data to calculate a change in the heliostat azimuth and elevation encoder reference or "mark" positions to minimize the time-variant tracking errors. This approach has also been referred to as "biasing" the heliostat, where the bias values are synonymous terms for the position of the encoder reference marks in the plant coordinate system. Slightly differing approaches to this strategy have been used at Solar One and Solar Two.
- **Move** – Tricking the control system by changing the database location of the heliostat (without physically moving it) based upon tracking accuracy data. This introduces a constant shift in the beam, intended to minimize, not eliminate, the time-variant tracking errors by "centering" the beam's path about the desired aim point. This strategy is a new proposal and has never before been used.
- **Correction Model** – Implementation of an error-correcting model in the heliostat control system that eliminates time-variant tracking errors. This requires many tracking accuracy measurements over a day to calculate the magnitude of each error source. Once implemented, however, it need only be updated when encoders are replaced. This approach has been used before with prototype heliostats.

The first two strategies are easily implemented in the current control system, but actually serve only to minimize the problem, not solve it. The third strategy solves the problem and can achieve a very high tracking accuracy (0.5 mrad RMS or better). It appears this would be the preferred approach to use on the commercial plant. It is difficult, however, to implement in the Solar Two heliostat control system. The current study focused on the performance of the bias and move strategies, but further discussion of the correction model strategy is also provided later for comparison. For all strategies, the heliostat tracking accuracy at a point in time would be measured with the Beam Characterization System at the Solar Two site. Mavis[9], King[10], and Strachan[11] describe the BCS.

4.2.2.2. Performance Metrics

For each strategy and variation, a number of annual-average metrics was computed to evaluate performance and the change in performance from the strategy currently used at Solar Two. The annual-average metrics calculated include:

- RMS tracking error – total of horizontal plus vertical axes
- RMS vertical tracking error
- Peak tracking error – total of horizontal plus vertical axes.

Multiple metrics were used to better characterize the performance of a heliostat field with time-variant tracking errors. The annual-average RMS track error indicates the average tracking performance over the year. The RMS vertical error is of interest because it reflects the tendency to spill light onto the oven covers located above and below the receiver. This can damage the oven covers and cause a plant outage, whereas horizontal tracking errors tend to cause spillage that misses the receiver and oven covers altogether. The peak error metric is valuable in evaluating the annual-average of the worst daily tracking errors.

4.2.2.3. Modeling Approach

A geometric error model was developed that predicts the tracking error of a single heliostat over the course of a single day based on inputs such as the location, pedestal tilt, canting error, and encoder reference error. Stone (1998) describes the error model in more detail. To evaluate strategies for improving heliostat tracking, decisions must be based on more information than how the strategy affects a lone heliostat on a single day. Ideally, the strategies would be compared based upon their effect on the tracking of the entire field of heliostats on an annual basis. Unfortunately, no computational tools exist to perform the desired annual analysis. Instead, an estimate of annual performance was made by a weighted averaging of results from many runs of the single heliostat, single day model. To limit the analysis to a reasonable degree, only a single heliostat error profile was considered, but multiple heliostat locations, days of the year, and BCS measurement times were averaged. Table 19 lists the values of the control variables and their respective weighting factors that were used in this analysis.

Table 19. Control Variables for Annual Performance Metrics

Heliostat Location		Day Evaluated		BCS Measurement Time (Solar Time)			
Values	Weighting Factor	Values	Weighting Factor	North and South Heliostats	Weighting Factor	East Heliostats	Weighting Factor
1000 ft. North (N)	0.38	Summer Solstice (SS)	0.25	10:00	0.33	12:00	0.33
800 ft. East (E)	0.51	Equinox (EQ)	0.5	12:00	0.33	14:00	0.33
400 ft. South (S)	0.11	Winter Solstice (WS)	0.25	14:00	0.33	16:00	0.33
Total	1.0	**Total**	1.0	**Total**	1.0	**Total**	1.0

The heliostat location weighting factors represent the actual percentages of heliostats in each quadrant of the field. It is assumed that the performance of the east heliostat is representative of a west heliostat because of the geometrical symmetry, so the 0.51 weighting factor is representative of the number of heliostats located in both the east and west quadrants at Solar Two. The 3 days evaluated in the study are typically used for solar energy analysis because they represent the outer bounds (SS and WS) and the midpoint (EQ) of the sun's movement. Equinox received double the weighting of the other days because it occurs twice each year. For all cases, the day was assumed to be 12 hours long for the computation of daily RMS tracking error. The time of the BCS measurements is similar in that it represents the outer bounds and the midpoint of a 4-hour time window appropriate for each quadrant. These time windows reflect the constraints currently in use at Solar Two.

The geometrical error profile used for every heliostat was a 0.5-mrad pedestal tilt in the northeast direction. This tilt magnitude was the average value from 16 measured at random in the field. The results scale linearly, so the effects of a different magnitude tilt can be calculated by simply multiplying the results shown here by the ratio of the new to old tilt magnitude. For this study, the tilt was chosen to be in the northeast direction so that tilt components in both the north south and east-west directions were present for every heliostat location evaluated. Different tilt directions will change the character of the tracking error[12], but it is assumed that the distribution of tilt directions expected for the Solar Two field would be accounted for by the extensive averaging done in this study. Additionally, the use of daily RMS values in the calculations of two metrics minimizes the need to simulate every possible error profile since many error profiles have similar RMS tracking error values[12]. Since there is no good estimate of a representative magnitude for canting tilt error or encoder reference error available, none were assumed. For these reasons, simply increasing the magnitude of the tracking error results based solely on pedestal tilt can approximate the impact of these other error sources.

Annual-average performance is estimated by a weighted average of the daily performance for different field locations, days of the year, and times of the day for BCS measurement. For example, the annual-average RMS track error calculation for the Bias-3/D-4/Y strategy is shown in Equation 4.2.1. In this equation, RMS stands for the daily root mean square tracking error, and the subscripts represent the heliostat's field location, the day of year, and the time of day that the single BCS measurement was taken (Table 20). The calculations of metrics for other strategies differ, but equations are not shown here for purposes of brevity. The inherent assumption is that the random distribution of dates and times of the BCS measurements to be expected in practice is sufficiently represented by this type of averaging.

Table 20. Strategies Evaluated

Strategy	BCS Measurements per Day	Repeats per Year
Bias-1/D-4/Y	1	4
Move-1/D-4/Y	1	4
Bias-1/D-1/Y	1	1
Move-1/D-1/Y	1	1
Bias-3/D-1/Y	3	1
Move-3/D-1/Y	3	1
Bias-3/D-4/Y	3	4

Before calculating the tracking error for each daily case, one or more BCS measurements were first used to either adjust the mark position or calculate location offset value. These adjustments were calculated using an iterative, numerical approach. More specifically, a forward-difference, quasi-Newton approach was used with a convergence criteria of 0.001 mrad required for five consecutive steps. Basically, the mark position or X,Y, and Z location offsets, depending upon the strategy, were changed in small increments until the desired output was minimized. In the case of the 1/D strategies, the tracking errors were minimized for a single time of the day. For the 3/D strategies, the RMS tracking error as calculated from three times of the day was minimized. Table 20 lists the three times selected. For the north and south field, the three measurements are taken at 10:00, 12:00, and 14:00 solar time.

$$\begin{aligned}RMS_{Ann\ Avg} = {} & 0.38\left[\begin{array}{l}0.25\left(\dfrac{RMS_{N,SS,10}+RMS_{N,SS,12}+RMS_{N,SS,14}}{3}\right)+0.5\left(\dfrac{RMS_{N,EQ,10}+RMS_{N,EQ,12}+RMS_{N,EQ,14}}{3}\right)+\\ 0.25\left(\dfrac{RMS_{N,WS,10}+RMS_{N,WS,12}+RMS_{N,WS,14}}{3}\right)\end{array}\right]\\ & +0.51\left[\begin{array}{l}0.25\left(\dfrac{RMS_{E,SS,12}+RMS_{E,SS,14}+RMS_{E,SS,16}}{3}\right)+0.5\left(\dfrac{RMS_{E,EQ,12}+RMS_{E,EQ,14}+RMS_{E,EQ,16}}{3}\right)\\ +0.25\left(\dfrac{RMS_{E,WS,12}+RMS_{E,WS,14}+RMS_{E,WS,16}}{3}\right)\end{array}\right]\\ & +0.11\left[\begin{array}{l}0.25\left(\dfrac{RMS_{S,SS,10}+RMS_{S,SS,12}+RMS_{S,SS,14}}{3}\right)+0.5\left(\dfrac{RMS_{S,EQ,10}+RMS_{S,EQ,12}+RMS_{S,EQ,14}}{3}\right)\\ +0.25\left(\dfrac{RMS_{S,WS,10}+RMS_{S,WS,12}+RMS_{S,WS,14}}{3}\right)\end{array}\right]\end{aligned}$$

[Equation 4.2.1]

4.2.2.4. Variations on Bias and Move Strategies

For each of these strategies, different variations were considered in terms of the number of BCS measurements taken over the day and the number of times the strategy was repeated each year. Table 20 lists the variations. The numbers at the end of each strategy name contain the information found in the following columns, so reference to a "1/D-4/Y" strategy later in this report means a strategy that requires one BCS measurement per day repeated four times per year. At Solar One, a mark position adjustment strategy using three measurements over the day was used[7][9]. At Solar One, the BCS was automated to help take large numbers of measurements. The automation of this system was complicated and it experienced conflicts with the master control system that limited its use. For these reasons, a simple, PC-based system was installed at Solar Two. The Bias-1/D-4/Y strategy represents the approach used at Solar Two and was selected to reduce the labor requirements and to encourage high quality over high quantity in the BCS measurements performed each day. It was also believed that if the one BCS measurement needed in this approach was performed (optimizing tracking accuracy) at a time of day when that heliostat was likely to deliver the most power to the receiver, the integrated daily energy delivered to the receiver would also be maximized. For this reason, time guidelines were set for biasing each quadrant of the field based upon when the combined solar insolation and cosine performance were maximal.

4.2.3 Results

4.2.3.1. Bias and Move Strategy Results

Table 21, Table 22, and Table 23 list the results of the study, a compilation of 243 individual daily runs. A reduction in tracking error is beneficial, so a negative change from the current strategy is desirable. Because of the assumptions and averaging used in this study, there is some uncertainty in the results. It would therefore be inappropriate to differentiate between strategies with small differences in performance. The annual-average RMS tracking error results have the least uncertainty of the three because of the previously mentioned fact—many error profiles have similar RMS tracking error magnitudes. This makes the selections of the control variables and the error profile less significant. Conversely, the annual-average vertical error results have more uncertainty because they are more influenced by the choice of error profile.

Table 21. Annual Average RMS Tracking Error

	Heliostat Location				
Strategy	**North**	**East/West**	**South**	**Field Average**	**Change From Current Strategy**
Bias-1/D-4/Y	0.42	0.50	0.50	0.47	0.0%
Move-1/D-4/Y	0.39	0.45	0.51	0.44	-8.2%
Bias-1/D-1/Y	0.45	0.52	0.51	0.49	4.5%
Move-1/D-1/Y	0.41	0.51	0.53	0.48	1.3%
Bias-3/D-1/Y	0.40	0.48	0.48	0.45	-5.1%
Move-3/D-1/Y	0.37	0.46	0.48	0.43	-10.7%
Move-3/D-1/Yb	0.47	0.48	0.43	0.47	-0.4%
Bias-3/D-4/Y	0.37	0.44	0.44	0.41	-13.7%

Table 22. Annual Average RMS Vertical Tracking Error

	Heliostat Location				
Strategy	**North**	**East/West**	**South**	**Field Average**	**Change From Current Strategy**
Bias-1/D-4/Y	0.36	0.31	0.41	0.34	0.0%
Move-1/D-4/Y	0.34	0.23	0.43	0.29	-17.7%
Bias-1/D-1/Y	0.36	0.35	0.40	0.36	4.5%
Move-1/D-1/Y	0.34	0.32	0.43	0.34	-2.0%
Bias-3/D-1/Y	0.31	0.31	0.35	0.31	-9.5%
Move-3/D-1/Y	0.28	0.31	0.35	0.30	-14.4%
Move-3/D-1/Yb	0.36	0.32	0.30	0.33	-3.0%
Bias-3/D-4/Y	0.32	0.28	0.37	0.30	-13.7%

Table 23. Annual Average Peak Tracking Error

Strategy	Heliostat Location: North	East/West	South	Field Average	Change From Current Strategy
Bias-1/D-4/Y	1.11	0.85	0.77	0.94	0.0%
Move-1/D-4/Y	0.64	0.67	0.84	0.68	-38.9%
Bias-1/D-1/Y	1.13	0.91	0.81	0.98	3.8%
Move-1/D-1/Y	0.66	0.73	0.87	0.72	-31.6%
Bias-3/D-1/Y	0.57	0.88	0.69	0.74	-27.2%
Move-3/D-1/Y	0.54	0.60	0.69	0.59	-60.7%
Move-3/D-1/Yb	0.65	0.79	0.63	0.72	-31.5%
Bias-3/D-4/Y	0.55	0.88	0.65	0.73	-29.3%

For most metrics, the overall magnitude of the tracking errors is approximately 0.5 mrad on an annual basis, a comparable value to the tilt magnitude used in the error profile. The annual-average peak error, however, was much higher, averaging approximately 0.9 mrad, with the worst daily result from the 243 runs (not shown) of 1.8 mrad. These tracking errors, however, are lower than typically measured at Solar Two. A recent survey of historical BCS measurements indicated that the field RMS tracking error, when using one BCS measurement from each heliostat, was about 7 mrad rather than the 0.5 mrad obtained from this error profile based upon the pedestal tilt measurements of 16 heliostats. Likely, the other two error sources, alignment plane and encoder reference error, are significant contributors. It is also possible the sample of 16 randomly selected heliostats did not provide an accurate measure of the average pedestal tilt magnitude. In either case, the results should scale linearly so the relative differences between strategies should still be applicable to Solar Two.

One interesting result is that the 1/D-4/Y strategies perform better for every metric than the equivalent 1/D-1/Y strategies since they are updated seasonally. The effect of seasonal updates are less effective for strategies with three BCS measurements per day (compare Bias-3/D-1/Y to Bias-3/D-4/Y), most likely because some of the benefits inherent in averaging multiple measurements are already provided.

Additionally, the Bias-3/D-1/Y strategy performance beat the Bias-1/D-4/Y performance in every metric, especially the annual-average peak error. This is an interesting result since these two strategies require approximately the same labor time to implement. The Bias-3/D-4/Y strategy was slightly better, but it requires much more labor to implement. There are a number of intangible factors to consider, however, in the competition between these two strategies. For instance, one advantage of the Bias-1/D-4/Y strategy over the Bias-3/D-1/Y is that the heliostat is revisited often over the year. This is valuable because it increases the chance a BCS operation will locate a heliostat with an undiagnosed hardware problem, thereby indirectly increasing the field's tracking accuracy and performance. Another intangible benefit of the Bias-1/D-4/Y approach over the Bias-3/D-1/Y approach is that it minimizes tracking errors during the times of the day when the most power is transferred by the field. For example, an east field heliostat transfers more power to the receiver from 12:00 to 16:00 than from 8:00 to 12:00 solar time because the incident angle of the sun is smaller, leading to lower cosine losses and a smaller beam size. However, this effect is not accounted for in any of the metrics because the analysis required to do so was beyond the scope of this study.

Another interesting result is found by comparing the Bias and Move strategies. Upon first inspection, it appears that the Move strategy is clearly superior to the Bias strategy, independent of the frequency of execution. To verify this conclusion, strategy Move-3/D-1/Y was investigated. It differs from Move-3/D-1/Y only in that a different pre-existing bias value (mark position) was used in the daily performance runs. The conclusion drawn is that the performance of the move strategies is highly dependent upon the pre-existing heliostat bias value. One may further infer that the Move-1/D-4/Y strategy had superior performance to the Bias-1/D-4/Y strategy only because of the pre-existing mark position that was assumed in that case. The Bias strategies appear to be less dependent on the pre-existing mark position than the Move strategies, an advantage since every heliostat at Solar Two has a pre-existing bias value.

4.2.3.2. Correction Model Strategy

Tracking control technology has improved since Solar One was developed. Current state-of-the-art technology permits heliostat-tracking accuracy of 0.5 mrad RMS or better over the day without adding costly design requirements on the heliostat mechanical and structural systems[8]. This approach of using an error-correcting model involves the following steps:

- Develop a heliostat error model in the plant coordinates
- Obtain tracking accuracy data for every heliostat by taking approximately 20 BCS measurements in a day
- Estimate error parameters from the track data
- Use the error parameters to modify the tracking commands so that the reflected beam will be incident upon the desired aim point.

Figure 40 shows an example of the achievable tracking accuracy. Sandia took this data in 1982 during the Second-Generation Heliostat Program[11]. The elevation track error is reduced by more than a factor of 10 and the azimuth error is reduced by over a factor of 2. This approach has also been successfully used on solar dish concentrators to improve the tracking accuracy by a factor of 20[7]. Another advantage of the correction model over the Bias and Move strategies is that it properly handles south field heliostats that undergo singularity. Stone and Lopez[7] explain how the bias strategy can be severely flawed for heliostats that undergo singularity.

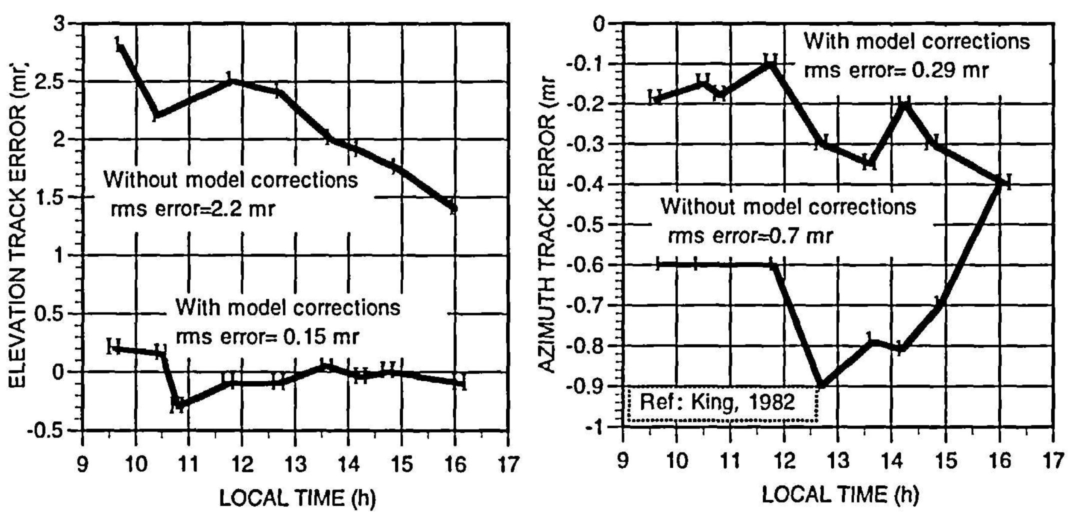

Figure 40. Tracking Errors of a Prototype Heliostat were reduced by a Factor of 10 using the Correcting Model Strategy

The advantage of the correction model is that once implemented, it adjusts the heliostat tracking to correct for the geometrical error sources and prevent time-variant tracking errors. It is effective at all times of the day and all seasons. Although it takes many BCS measurements to implement, the model requires updating only when the azimuth or elevation reference positions change, for example when an encoder or limit switch is adjusted or replaced. This update to the error model can be made with fewer tracking accuracy data points (possibly as few as three BCS measurements over a day). Previously, it was thought that expensive hardware changes would be required at Solar Two to implement such a system. An innovative approach, however, could probably be developed to implement such an approach with changes only to the software, not the control system hardware. Additionally, about 20 BCS measurements per heliostat would be required to fit the error model parameters. The BCS measurements and software changes would take approximately 6 months to implement if proper resources were allocated.

4.3 Conclusions and Recommendations

The main objectives of Solar Two were originally focused on the proof of concept of the molten salt portion of the plant. Recent performance data shows that Solar Two met the thermal to electric conversion and parasitic energy use goals. The energy collection performance, however, is falling 10 to 20 percent short of the goals and endangering the future of the technology. The 7 mrad RMS field tracking error is likely a large contributor to this shortfall, so improving heliostat tracking accuracy has become crucial.

Three significant error sources that adversely affect heliostat tracking accuracy at Solar Two were identified: azimuth tilt, mirror alignment/canting, and encoder references. Three strategies were developed to address these error sources. Although they have not yet been tested on the heliostats, when these strategies were analyzed with the heliostat tracking model they were found to increase tracking accuracy.

The study of the strategies has shown that, for approximately equal labor use, the Bias-3/D-1/Y strategy appears to provide slightly better performance than the Bias-1/D-4/Y strategy currently used at Solar Two. However, the complexity of the calculations prevented the use of an annual-average RMS tracking accuracy metric that includes incident-power weighting, a factor that could help the performance of the Bias-1/D-4/Y strategy compared with the Bias-3/D-1/Y strategy. Further experimentation and analysis would be beneficial in understanding the competition between these two strategies.

The newly proposed Move strategy appeared superior to the Bias strategy in some cases, but inferior in other cases because of a strong dependence on the pre-existing mark position of the heliostat. For this reason, it is not recommended for implementation.

Based on the results of this study, the implementation of an error correcting strategy into the control system is recommended for the commercial plant.

5.0 Summary

The main objectives of this Solar Two project were to demonstrate that the technology worked as predicted and to resolve problems that might affect future commercial plants. The plant served that purpose well—identifying the issues and solutions needed to build the next plant successfully. As anticipated in a pilot plant, problems associated with specifics in design, construction, and operation were encountered, including several component failures that resulted in temporary plant outages. None pose any significant threat to the technology. Solutions were found for most issues through design improvements, improved quality control during construction, or modification to operating and maintenance procedures. Most solutions were implemented at Solar Two, but a few are significant enough in scope that they can only be implemented in the next plant. In those cases, workarounds were identified that allowed continued successful operation and testing at Solar Two.

Identifying key issues and their resolution has, in itself, been an important accomplishment of Solar Two. The resulting data will allow performance models to be refined and the performance of future commercial plants predicted with enough confidence to attract investment in the technology.

Key Findings

Some of the key accomplishments of the Solar Two project include:

- **Efficiency** – The receiver efficiency matched its design specification of 88 percent in low-wind condition and matched modeled results in high winds. The efficiency of the thermal storage system also matched it design goal of >98 percent efficiency. (Outcomes and conclusions for receiver efficiency and thermal storage testing are provided in Sections 2.2 and 2.3 of this report.)
- **Parasitic Power Use** – The electrical parasitic energy load, the electricity required to run the plant, was reduced by 27 percent, demonstrating that the plant routinely met its design goal. (Outcomes and conclusions for parasitic power consumption testing are provided in Section 2.4 of this report.)
- **Dispatchability** – Using its unique and extremely efficient thermal storage system, Solar Two delivered electricity to the grid around the clock for 153 consecutive hours. (Outcomes and conclusions for dispatchability testing are provided in Section 2.5 of this report.)
- **Energy Production** – Solar Two produced 1,633 megawatthours (MWh) over a 30-day period, exceeding its 1-month performance measure of 1,500 MWh set by the U.S. Department of Energy. The plant also produced a record turbine output of 11.6 MW.
- **Reliability** – During the summer of 1998, the plant operated for 32 of 39 days (4 days down because of weather, 1 day because of loss of offsite power, and only 2 days for maintenance), representing a 94 percent run-day availability.

Notes

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Appendix I

Solar Two Project Test and Evaluation Plan

Volume I and II

Appendix I

Solar Two Project Test and Evaluation Plan

Volume I and II

SOLAR TWO PROJECT

Test and Evaluation Plan
Volume 1

No.	DATE	REVISIONS	BY	CH'K	APPR.
0	5/11/95	Issued for Implementation	TAC-Subcommittee		
B	4/21/95	Issued for Approval	TAC-Subcommittee		ABZ
A	2/8/95	Preliminary	TAC-Subcommittee		N/A

ORIGIN Bechtel Corp.	**SOLAR TWO PROJECT** Daggett, California Test and Evaluation Plan	**Job No. 21948** Document Number: 3PS-G-003	Rev. 0

Table of Contents

Section **Page**

1.0 Introduction

This document, the Solar Two Test and Evaluation Plan, outlines the key tests, data reductions, and evaluations to be performed on the Solar Two plant. It also defines the organization and schedule for these activities.

Solar Two is a solar central receiver electric power generating plant using molten nitrate salt as a receiver coolant and storage medium. Solar Two will be constructed using portions of the installation known as Solar One. Solar Two will have the same maximum electrical output, 10 MWe net, as Solar One, but will demonstrate the commercial readiness of molten salt technology. Figure 1-1 shows the key features of Solar Two.

Methodology

The tests and evaluations presented in this document are based on risks identified during the Utility Studies [Reference 3-1]. The methodology for relating the Utility Studies to the Solar Two Program and the mitigation of risk for a 100 MWe commercial Power Tower is shown in Figure 1-2. The intent is to provide lessons learned and design information which directly impact future design reliability and cost-effectiveness.

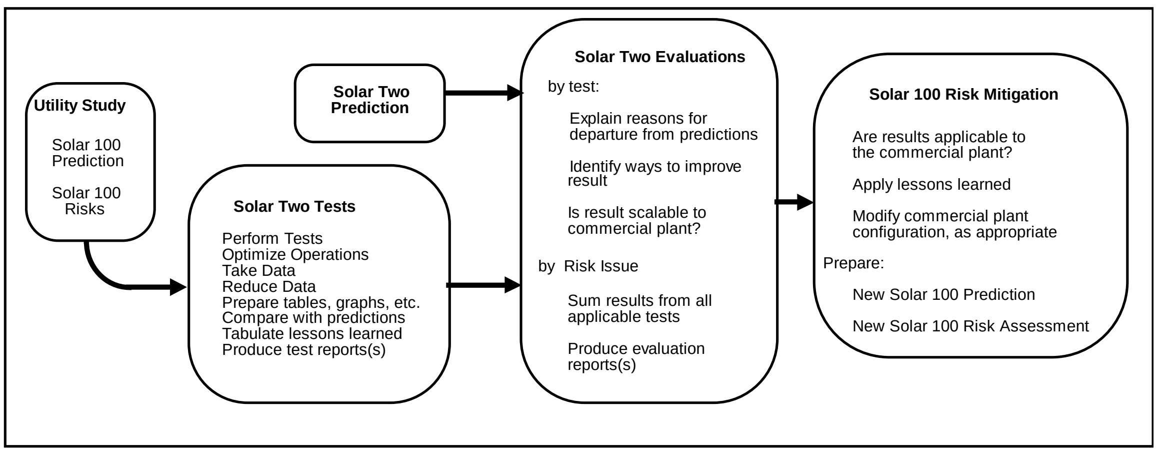

Figure 1-2. Test and Evaluation Plan Methodology

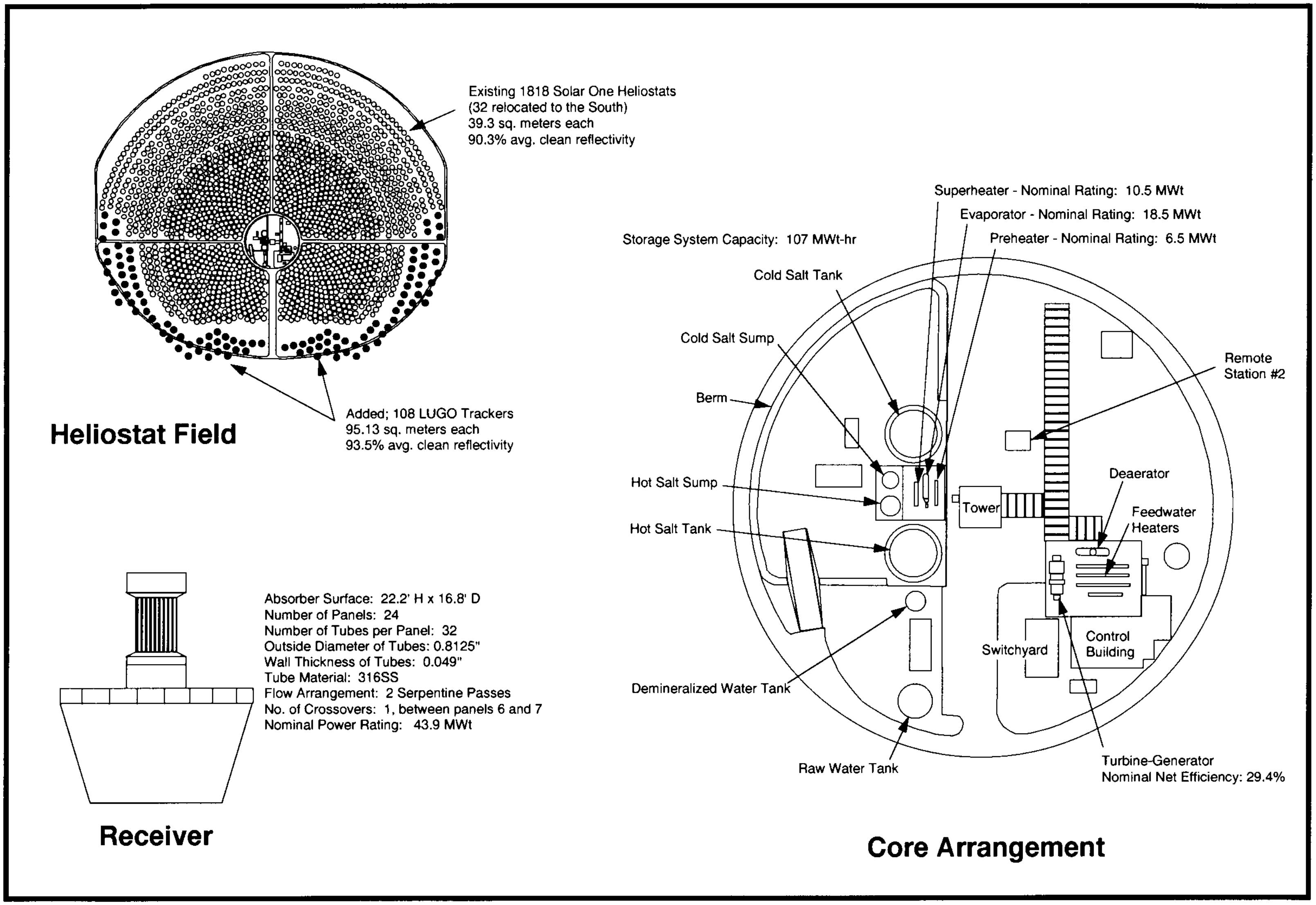

Figure 1-1. Key Features of Solar Two

2.0 Objectives

The objectives of the Solar Two Test and Evaluation Plan derive from the Solar Two Project Objectives.

Solar Two Project Objectives

The objectives for the Solar Two project as outlined in the Design Basis Document [eight sections] are:

1. Validate the technical characteristics (reliability, annual net electric performance, minimal environmental impact, and capability for dispatch) of the nitrate salt receiver, storage system, and steam generator technologies.
2. Improve the accuracy of economic projections for commercial projects by increasing the database of capital, operating, and maintenance costs.
3. Simulate the design, construction, and operation of the first 100 MWe (or larger) power plants.
4. Collect, evaluate, and distribute to US. utilities and the solar industry the knowledge gained to foster wider utility interest in the first commercial projects.
5. Stimulate the formation of a Commercialization Consortium that will facilitate the financing and construction of the initial commercial projects.

The Test and Evaluation Plan addresses objectives 1, 2, and 4. Objective 3 will be supported to the extent possible. Objective 5 is not part of the Test and Evaluation Plan.

Scope

The scope of the Test and Evaluation Plan is limited to testing and evaluating Solar Two. While some data deliverables will aid in assessing the status of the technology as a whole, the majority of the research performed under the Test and Evaluation Plan will be directed toward developing a better understanding of Solar Two and improving its performance. Studies which predict the performance of future plants will be conducted under the auspices of another plan. The scope of the Test and Evaluation Plan is:

1. Define the tests and evaluations required to meet the test and evaluation objectives.
2. Define the support staffing and equipment requirements to accomplish objective 1.
3. Define the schedule and budget for performing tests and evaluations.
4. Define the deliverables resulting from work conducted under the Test and Evaluation Plan

3.0 Test and Evaluation Plan Summary

3a. Status of Solar Two Technology

Molten salt was selected as the preferred system concept for central station solar thermal electric power production during the Utility Studies (Reference 3-1).

A risk assessment for the first commercial plant (Solar 100) was conducted during Phase II of the utility studies. A group of over 30 central receiver technology experts were convened in workshop sessions. They identified potential risks, quantified the expected impact on the value of Solar 100 and evaluated and recommended specific risk mitigation efforts. Their conclusion was that the risk of building a commercial plant then was large; they predicted that the value of the plant, in terms of expected revenue would have been only 18 percent of calculated value without further development (Reference 3-2). Since the economics predicted for the commercial plant was marginal without considering this risk, the need for risk mitigation became most important.

A system experiment employing the Solar One facility reconfigured to utilize molten salt for energy collection and storage was one of the main recommendations of this study (Reference 3-3). This recommendation resulted in the present Solar Two project. The risks identified for Solar 100, without risk mitigation, are summarized below:

By Subsystem	
Subsystem	**Expected Impact, %**
Overall Plant	2.2
Collector	11.0
Receiver	42.7
Tower-EPGS-BOP	0.7
Heat Transport	5.6
Thermal Storage	7.3
Steam Generator	4.6
Master Control	7.9
Total	82.0
By Effect	
Effect	**Expected Impact, %**
Capital Cost	22.5
Maintenance Cost	13.1
Performance/Outage	46.4
Total	82.0

The 82 percent shown above is the expected reduction in plant value (revenue) of a first commercial plant built with the then-current technology status. Since there has been little technology development following the completion of the utility studies (1988), this is representative of the present technology status.

3b. Solar 100 Risks

A summary of the specific technical uncertainties causing the high level of risk to Solar 100 is shown on Table 3-1. This table summarizes the risks by effect and by the subsystem causing the risk. The impact is coded from 1 to 5 with 1 representing less than a 1 percent reduction in plant value and 5 representing an impact greater than 10 percent. It can be seen that the receiver is the major risk element in this system. The main sources of risks are (1) high capital costs, (2) equipment failures, (3) operational uncertainties, (4) low efficiency in solar energy collection and (5) high parasitic power usage.

The collector system represents the major source of capital cost uncertainty. Since no new heliostats are being procured for Solar Two, this project can do little to mitigate this risk. The other cost risks for Solar 100 are largely outside of the scope of the test and evaluation plan.

The general approach to using the Solar Two test and evaluation program to mitigate Solar 100 risks is shown on Figure 1-2. The Utility Studies are the starting point for each specific design or performance issue; the Solar 100 prediction and perceived risk forms the basis for the test and evaluation conducted in the Solar Two program. The appropriate tests will be conducted to measure the effect and compare it to predictions. Optimizations will be conducted to maximize system performance. The lessons learned will be tabulated and a test report prepared. The evaluation program will attempt to explain reasons for any departure of test results from predictions and will try to identify means to improve the results in a commercial plant design. The evaluation program will also assess the scalability of the measured Solar Two results to the commercial plant. These evaluations will be documented. The Solar 100 risk mitigation effort will be completed by assessing the applicability of these results to Solar 100, applying the lessons learned to the Solar 100 design and modifying the prediction and risks of the specific issue to Solar 100.

3c. Test Program Summary

The Solar Two test plan is constructed to address all of the risk issues for Solar 100. The test program will be conducted in five successive Phases:

- **Phase I** – Familiarization.
- **Phase II** – Characterize Solar Two as built.
- **Phase III** – Optimize the operation of Solar Two to produce maximum performance. Also, identify and simulate, where possible, improvements to the design of the commercial plant.
- **Phase IV** – Measure Solar Two performance under optimum operations simulating a commercial plant.
- **Phase V** – Extended operations or post-test examination.

The largest risk to the commercial system, as shown in Table 3-1, is reduced performance and forced outages, both of which reduce the revenue from the plant. The tests and evaluations planned to reduce this risk issue are:

3d. Potential Solar Two Risks

3d.1 Equipment Failures

Plant unavailability due to equipment failure is a major risk issue. Most of this data will need to be collected in Phase III in an extended period of operation in order to produce statistically meaningful and relevant information. However, for the risks due to potential leaks of the thermal storage tanks, measurements during the filling of the tanks need to be taken. Also, tests and evaluations conducted during Phase II will determine the duty cycle and applicability of specific components to the commercial plant. For example, even though Solar Two may continue to need electric trace heating for thermal conditioning of salt lines and equipment, if Phase II identifies and confirms an improved mode for thermal conditioning, this failure data will be excluded from the evaluation of the commercial plant's risks. Data will be collected as specific Mean Time Between Failure (MTBF) and Mean Time To Repair (MTTR) for each component rather than only as plant availability.

3d.2 Operational Problems

Operational problems were identified as a significant performance risk issue. During previous experiments, much potential energy collection was lost because the system was not ready for start-up at sunrise or start-up and restart transitions were lengthy. All operational issues will be addressed in Phase I to characterize the as-built Solar Two configuration. Major tests during Phase II will be devoted to increasing plant performance through improved plant operations. The performance for the optimized plant will be measured during Phase III.

3d.3 Collection Efficiency

Reduced energy collection due to reduced collection efficiency was also identified as a significant risk issue. The two major concerns are degradation of collection efficiency over time and a derating of the allowable collection temperature due to flux imbalances on the receiver. Specific Phase I and Phase II tests will be devoted to these measurements and to identify the most appropriate response to any losses.

3d.4 Parasitic Power Usage

All previous experiments had high parasitic power consumption. Measurements will be made of both thermal and electric power consumption and losses. Tests will be conducted during Phase II to identify operations and/or configurations which reduce parasitic losses. Statistically meaningful data will be generated during Phase III operations.

3d.5 High Maintenance Costs to Repair/Replace Failed Equipment

Equipment failure produces a significant risk to maintenance costs as well as the performance loss due to plant outage discussed above. Most of the data collected for the performance loss evaluation (MTBF and MTTR) will be applicable here. In addition, the spare part and other consumables and the labor skills and time required to effect repairs will be tabulated. These will all be collected into a maintenance log kept throughout Phase III.

A summary of the Solar Two tests, the risk issues addressed and the test program Phase is given in Table 3-2.

3e. Evaluation Plan Summary

The evaluation plan is designed to (1) use the measured test results to update the technology status, (2) identify ways to improve the technology and (3) relate the results to the commercial plant.

A summary of the Solar Two evaluation plan is shown on Table 3-3. Each specific evaluation is related to the tests utilized and to the risk issues addressed.

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Table 3-1. Solar 100 Risk Summary

Risk	Issue	Reason	Impact*/Subsystem Collector	Receiver	Thermal Storage	Steam Generator	Master Control
Capital Costs Performance/Outage	Higher Than Predicted Costs	Limited Cost Database	5	4	1	2	1
	Equipment Failures						
	Heat trace	Previous experience		5			
	Salt valves	Cold stroke, erosion, etc.		4		2	
	Receiver panels	Limited experience with 316H SS		2			
	Storage tank leaks	Corner junction failure or shock			3		
	Steam generator tube-tubesheet leaks	Salt corrosion				2	
	Operational Problems						
	Start-up readiness	Wind effects, salt lines “cold”		5			
	Long start/restart times	Unknown warm-up and transient capab.		5			
	Inadequate collector/receiver control	New requirement/interaction					2
	Poor weather prediction	Previous experience					2
	Collection Efficiency						
	Performance degradation	Wind, insul. degrad., coating, etc.		4			
	Derated performance	Flux imbalance on receiver		4			
	High Parasitic Power Usage	Many unknowns		5			
Maintenance Costs	**Replace/Repair Failed Equip.**		1				
	Heat trace	Costly to repair/replace		5			
	Salt valves	Moderate cost to repair/replace		3		1	
	Receiver panels/tubes	Limited experience		1			
	Absorptive coating	Must recoat and cure		2			
	Leaking storage tank	Could be major problem			1		
	Steam generator tubes	Moderate costs expected				1	

* Risk impact on Solar 100 plant value: 1 is <1%, 2 is 1%-3%, 3 is 3%-5%, 4 is 5%-10%, 5 is >10%.

Table 3-2. Solar Two Tests

Test	Description	Risk Issue	Phase
1. Clear day receiver loop operation.	Familiarize test engineering team with both manual and automated operation of the receiver loop. Measure receiver glint.	None. Familiarization only.	I
2. Steam generator operation and electric power production.	Familiarize test engineering team with manual and automated operation of the steam generator and the EPGS.	None. Familiarization only.	I
3. Steam Generator/EPGS characterization.	Develop a performance map for the steam generator and EPGS.	None. Measure performance. Qualify.	II
4. Transient operation with simulated clouds.	Measure transient response to cloud passage. Tune controls for optimum response.	Performance/operation/ inadequate control.	II and III
5. Heliostat patterns for receiver warm-up.	Develop heliostat aiming patterns which minimize start-up times for various times of day, seasons and wind conditions.	Performance/operation/long start times.	II and III
6. Receiver efficiency.	Measure the receiver's efficiency as a function of the operating temperature and wind conditions.	Performance/collection efficiency.	II
7. Receiver performance map.	Develop a receiver loop performance map as a function of the incident power, the wind conditions, the receiver operating temperature, and the time of day and season. Determine what conditions require derating of outlet temperature.	Performance/collection efficiency/derated outlet temperature.	II and III
8. Thermal losses.	Measure the thermal losses from the plant equipment and piping.	Performance/parasitics.	II and III
9. Parasitic electric power.	Measure the electric power consumption throughout the plant.	Performance/parasitics.	II and III
10. Receiver start-up following rain.	Determine what impact rain has on start-up readiness of the receiver.	Performance/operation/ start-up readiness.	II and III
11. Receiver drain during high wind conditions.	Determine whether high winds impact the drain time of the receiver.	Performance/operation problems.	II and III
12. Optimization of receiver loop operations.	Develop optimum operations for the receiver loop to maximize performance.	Performance/operation problems.	II and III
13. Overnight thermal conditioning.	Develop optimum methods to maintain system warm overnight.	Performance/equipment failures; /start-up readiness; /parasitics.	III

Table 3-2. Solar Two Tests (continued)

Test	Description	Risk Issue	Phase
14. Optimum plant operations.	Confirm the operating modes and simulations selected in phase II.	All receiver performance issues.	II
15. Power production and electric power.	Operate as a utility plant to produce maximum net output.	Performance/outage and maintenance costs.	III
16. Operation to demonstrate dispatchability.	Operate plant in the power production.	Performance/outage and maintenance costs.	III
17. Repeat of key efficiency tests.	Repeat selected efficiency measurements conducted in test 6 yearly.	Performance/collection efficiency/degradation.	III
18. Coupon corrosion and salt chemistry.	Measure chemical composition of salt periodically. Conduct metallographic examination of corrosion samples.	Outage/equipment failures.	III
19. Storage tank thermal stresses.	Measure the displacements and stresses in the storage tank wall and bottom joint.	Outage/equipment failures.	I
20. Extended operational tests.	Extended operational tests may be conducted to either add and test improvements identified during the T&E program or to further improve and demonstrate the as-built system. These are beyond the scope of current project.	As identified.	III
21. Post-test examination and evaluation.	Perform special tests which were not performed during the T&E program and any destructive examinations.	As identified.	III

Table 3-3. Solar Two Evaluations

Evaluation	Description	Risk Issue	Tests
Plant Availability	Use the forced outage rate for Solar Two and the measured MTBF and MTTR values to upgrade the design for Solar100. Use these measurements and the upgrades identified to predict a forced outage rate for Solar 100.	Performance/outage/equipment failures	12, 13, 14, 15, 16, 18, 19
Efficiency	Relate the measured Solar Two efficiency to the commercial plant. Identify potential improvements to the commercial plant's design.	Performance/collection efficiency.	6
Operability and Controllability	Relate Solar Two performance measurements to the commercial plant. Utilize the lessons learned in the test program to identify improvements for the Solar100 design.	Performance/operational problems.	4, 5, 7, 10, 11, 12, 13, 14, 15, 16, 17
Parasitics and Losses	Utilize the measurements of parasitic power consumption and thermal losses to improve the Solar 100 design. Predict the parasitics and thermal losses for the upgraded Solar 100 system.	Performance/high parasitic power usage.	8, 9, 12, 13, 14, 15, 16
Maintenance	Use the equipment failures in Solar Two to upgrade the Solar 100 design. Use the measured failure rates and repair times and skill requirements to develop a maintenance model for Solar 100. Use Solar Two operations to predict the requirements for Solar 100.	Maintenance costs.	14, 15, 16
Maintenance Costs	Use the maintenance requirements identified above to predict the O&M costs for Solar 100.	Maintenance costs.	14, 15, 16
Equipment Lifetime	Assess the equipment life expended during the T&E program. Relate to the commercial plant.	Costs.	14, 15, 16, 18, 19, 20
Environment and Safety	Aspects unique to safety and environmental protection of this technology will be reported.	None.	14, 15, 16

4.0 Test and Evaluation Organization

4a. Organization

The Solar Two Test and Evaluation Organization is depicted on Figure 4-1. The Roles and Responsibilities of the major positions are shown in the table. The Test and Evaluation Manager has primary responsibility for T&E activities at Solar Two and is the primary liaison with the Operation and Maintenance Contractor.

Test Engineers have the responsibility for detailed test planning, conduct of test, data evaluation and report preparation. A Lead Test Engineer will be identified for each test. The Lead Test Engineer will identify additional personnel support requirements including other Test Engineers and Operation and Maintenance (O&M) Contractor support.

The O&M Contractor has primary responsibility for plant operations and maintenance and for providing test support.

4b. Staffing Requirements

The Test and Evaluation Manager will be resident on site through the Test and Evaluation period, year 1 of Phase 6, and part time through the Power Production Phase, years 2 and 3 of Phase 6. The Test and Evaluation Manager and Test Engineer positions will be staffed from the Solar Two Participant Organizations. The Test and Evaluation Manager along with the SCE Project Director will be responsible for obtaining the additional Test Engineer personnel support from the Solar Two participants.

For the Test and Evaluation Phase, first year of operation, a core team of four Test Engineers are planned to be resident on the site. Data evaluation and report preparation may be performed on or off site. For the Power Production Phase, second and third years of operation the resident Test Engineer staffing will be as required to support specific tests.

4c. Interfaces

4c.1 O&M Contractor

The primary O&M Contractor interface for Test and Evaluation is through the Test and Evaluation Program Manager. Test planning, coordination and conduct of the discrete tests will be at the Test Engineer level with a O&M Contractor designated Lead Operator and Maintenance personnel contact.

The O&M Contractor has the primary responsibility for plant operations and maintenance, and overall responsibility for the safe operation of the facility. To this end the O&M Contractor shall identify and bring the attention of the Test and Evaluation Manager any test situation and/or requirement that could potentially place personnel or the plant at risk. The Test and Evaluation Manager in conjunction with the Project Director and the O&M Contractor will resolve the issue before proceeding with the test.

4c.2 Start-up Organization

The Engineering and Construction Management Contractor (ECM) Start-up organization is responsible for plant Start-up/Checkout and Acceptance, Phase 5, through final acceptance of the plant by Southern California Edison. Certain Test data is required during this time period e.g., Test No. 19. The Test and Evaluation Manager will coordinate with ECM Start-up Manager to plan and schedule test requirement and data gathering.

4c.3 Equipment Suppliers

The technical services of Solar Two Equipment suppliers may be required. The Test Engineer will identify requirements and arrange/coordinate with the Test and Evaluation Manager for site representation, if required. It should be noted there may be incurred costs to cover supplier's time and travel.

Discrete tests may have impact on equipment warrantees. The Test Engineer as part of the planning process shall identify any test requirements that place equipment warrantees at risk and reach resolution with the Test and Evaluation Manager, O&M Contractor and equipment supplier before proceeding with the test.

4c.4 Engineering

Interface with ECM engineering and/or other engineering groups will be on an as required basis. Support requirement will have to be defined and coordinated with the Test and Evaluation Manager and Project Director.

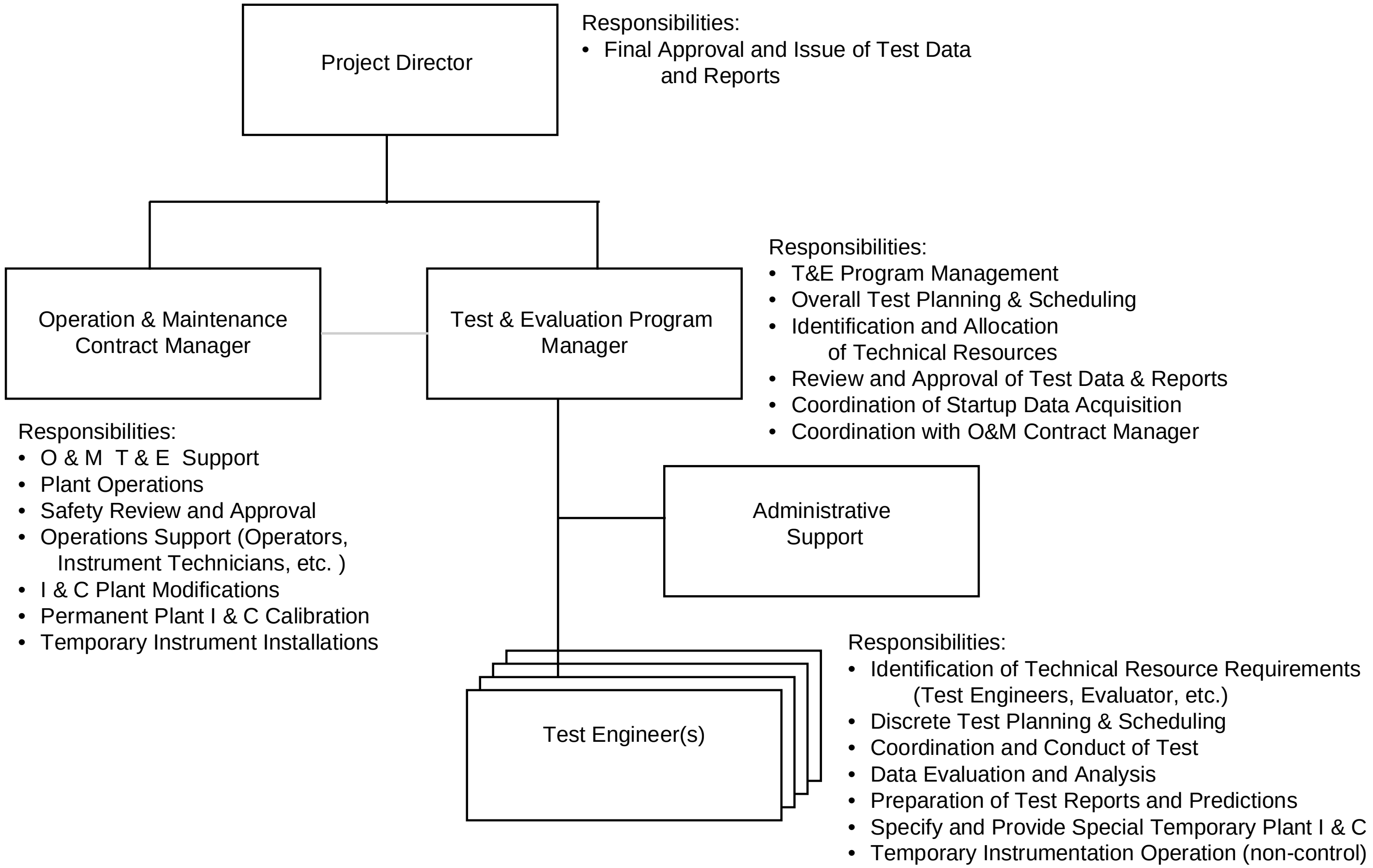

Figure 4-1. T&E Organization

5.0 Schedules

Introduction

The scheduling of tests in this Test and Evaluation plan must be flexible to accommodate changing weather conditions, equipment availability, time of day constraints and seasonal variations. The Test and Evaluation Plan is divided into five Phases: Phase I – Familiarization, Phase II – Characterization, Phase III – Optimization, Phase IV – Power Production, and Phase V – Post Operation. Within each of these phases, the order in which the tests are conducted depends on required conditions of the tests and state of the plant. Furthermore, some tests are complementary and can be done during, immediately after, or before other tests. Other tests have specific starting requirement or must have special instrumentation installed during construction. This section outlines these requirements and efforts to make the scheduling of the test easy and simple to understand. Tables 5-1, 5-2, 5-3, and 5-4 shows these requirements. Reference Volume II, Section 3.0 for Test and Evaluation Detailed Schedules.

5a. Description of Test and Evaluation Program Phases

Phase I to III: Familiarization, Characterization, and Optimization

Objectives: Measure and document the engineering and operational characteristics of the plant. Optimize plant operations to produce maximum net electricity production and to provide maximum flexibility in plant operation. Determine and tabulate lessons learned from these tests. Particularly focus on those area that could improve the potential for commercialization of this technology.

Tests Include: 1-14, 18 and 19.

Duration: Allow 12 months for these phases.

Phase IV: Power Production

Objectives: Demonstrate the annual performance from this plant. Demonstrate the ability of the plant to meet load demand through the use of the molten salt thermal storage system. Increase annual plant performance through improved operations.

Tests Include: 15, 16, and 17.

Duration: Allow a minimum of 2 years for this phase.

Phase V: Post Operation

Objective: Determine effects of system operation on the plant components' lifetime and on the salt properties. Provide more data on material characteristics during plant operation and performance to support commercialization of this technology. Additional tests could be added that have not been defined.

Test Included: Test 20, 21.

Duration: Allow 3 months, but this is after the Power Production Phase. Test 20 is beyond the scope of the Solar Two Project as now defined.

5b. Prerequisite Logic

The Test and Evaluation Program will commence as soon as the start-up and acceptance test program is completed. The information available and the condition of the plant at this time are assumed to be:

1. System descriptions, equipment and instrumentation lists, P&IDs, and other documentation are available and redlined as required.
2. Systems are installed and checked out.
3. Pre-start and Post-operation check lists have been compiled, verified, and redlined as required.
4. Acceptance tests are complete and documented.
5. Systems are capable of safe operation in all modes through all transitions in both a manual operating mode and in an automated mode.
6. All operating procedures for all modes and transitions have been confirmed and redlined, if required, for both manual and automated operation.
7. All of the DAS system in installed and checked out.
8. The O&M operating team is fully trained in plant operation.
9. The T&E team, including the test conductor, was on-site for the checkout and start-up phase, and they are familiar with the plant and its operation.
10. An adequate complement of spares is available.
11. It is assumed that data from the start-up phase is available and will be used for guidance in the test and evaluation phase. However, the majority of data required for individual tests will be collected in the five T&E Phases.

5c. Calendar of Activities, Sequencing of Tests and Duration

The five Phases will take place over a period of 3 years and 3 months. It is anticipated that the first three phases will be completed in the first year of operation. The power production phase will last 2 years. The post-operational phase will include post test examinations of components and materials in the plant. This phase will last 3 months or more if there is additional funding. Any post operational tests will be included in this phase also. Figure 5-1 shows the test program schedule.

Phase I – Familiarization Tests 1-3, part of 4, 5	3 months
Phase II – Characterization Part of Tests 4-8 and Tests 9-11	10 months
Phase III – Optimization Part of Tests 4, 5, 14, and Tests 12, 13	5 months
Phase IV – Power Production Tests 15-17	2 years or more

Phase V – Post Operation Tests 20, 21	3 months or more

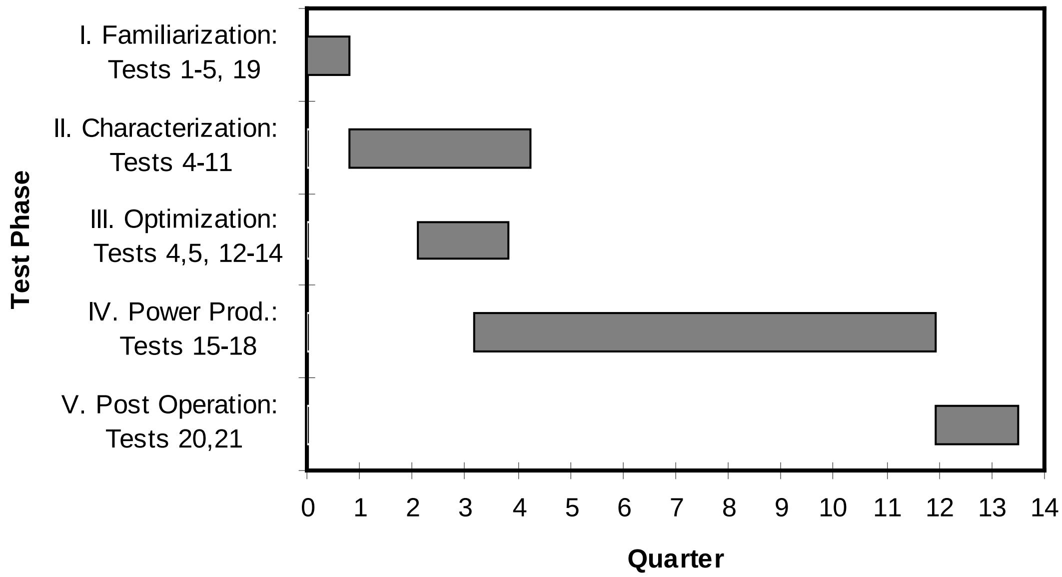

Figure 5-1. Schedule of Solar Two Test Phases

Setup for tests 18 and 19 will take place during the construction phase of the project. Data from 19 will be collected during the first year. Data from test 18 will be collected over the entire project.

Table 5-1 shows a preferred sequence to the tests, the duration which includes pretest planning, testing, and data evaluation. The pretest planning duration includes developing test procedures and calibration requirements. Testing duration is the time frame allotted to conduct the test. The data evaluation duration consists of the time to conduct onsite data reduction, offsite evaluation and publication, review and issuing of reports.

First Year Tests: Familiarization, Characterization, and Optimization

The sequence of the tests in the first three phases is shown in Table 5-1. This serves as a guide only. The order in which these tests are conducted is dependent on the weather, time of day, season, equipment availability and other tests. Complementary tests are listed in Table 5-1. Tests 1 through 5 are primarily for familiarization of the systems. They should be stand alone tests. Three months have been allotted for these tests. Tests 4 through 11 are included in the Characterization Phase for which 10 months have been allocated. It should be noted that several of these tests, though, can be conducted during or immediately following another test and partly done in Phases I, III, and IV. Most of these tests require sunny weather. Five months have been allocated for the Optimization Phase.

Second and Third Year Tests: Power Production

Tests from the previous year which were not completed could be finished in the second and third years. Two years are allotted for power production where the operation of the plant will simulate a commercial plant.

Post Third Year Tests: Post Operation

Test 21 is to completed after Power Production Phase of the plant so samples of materials can be removed. Test 21 should take 3 months. Additional operational tests (Test 20) could be added here.

5d. Weather, Time of Day, and Seasonal Requirements

The weather and time of day and seasonal requirements are shown Tables 5-2 and 5-3. Table 5-4 shows the major equipment availability and special instrumentation requirements.

- Test with Special Weather Requirements:
  - The following tests require sunny, clear weather: 1, 2, 4, 5, 6, 7, 10, 11, 12, 14, 15, 17, 19.
  - The following tests require intermittent partly cloudy weather: 12, 14, 15.
  - The following tests require windy conditions: 5, 6, 11, 12, 14, 15, 17.
  - The following test requires a recent rain: 10.
- Test with Time of Day Requirements:
  - The following test must be done symmetrically about solar noon: 6, 17.
  - The following test should be done at sunrise: 5.
  - The following tests must be done at various time throughout the day: 5, 7, 12, 14, 15, 16.
  - The follow should be done at night or during extended cloudy weather: 8, 9 (partly), 13.
- Tests with Seasonal Requirements:
  - The following tests should be conducted in the summer: 6, 17.
  - The following test should be conducted a few days in each season: 7.
  - The follow test should completed in one season only: 13.
- Test Which Can Be Conducted Independent of Weather:
  - These tests can be conducted independent of weather: 8, 9, 13, 18, 21.
  - If the hot tank is charged: 2, 19.

5e. Major System Availability Requirements

Master Control System Operational
Heliostat Field only
Test 5 requires only the heliostat field.

Receiver Loop Heliostat Field, and Thermal Storage System

The following tests require both the heliostat field and receiver loop to be available: 1, 4, 6, 7, 10, 12, 17.

Receiver Loop and Thermal Storage System

The following tests only requires the receiver loop: 11, 13.

Thermal Storage Only

Test 19 requires the thermal storage for initial tank warm-up and fill.

Steam Generator Systems, Electric Power Generation Systems, and Thermal Storage

The following require both the Steam Generator and Electric Power Generation Systems: 3, 16.

All Major Systems

The following require all major systems: 3, 8, 9, 14, 15.

Plant in Long Term Hold

The following requires that the plant be in standby with no systems operating (to remove samples): 18.

5f. Complementary Tests

Tests that can be conducted together or can be overlapped:

- 3 with 4
- 5 with 6, 10
- 6 with 11
- 7 with 10, 11
- 8 with 9, 12
- 9 with 12, 13, 14
- 13 with 14
- 15 with 16
- 18 with 21.

5g. Tests with Special Timing or Instrumentation Requirements

Special Time Requirements – Construction Phase

Tests 18 (Coupon Corrosion) and 19 (Storage Tank Thermal Stresses) require installation of special test fixtures and instrumentation to be installed during the construction phase. In addition, part of test 19 must be conducted during initial heat up and fill of the hot and cold tanks.

Special Instrumentation Requirements

- Test 1 requires a glint meter (photometer).
- Tests 5, 6, 8, 11, 17, require an infrared video recorder.
- Test 9 requires watt meters.
- Test 18 requires a corrosion coupon test fixtures.
- Test 19 requires strain gages installed on the tanks and a portable data acquisition system.

Table 5-1. Sequencing of Tests, Duration, Overlapping Tests, and Testing or Timing Requirements

Test	Phase	Sequence	Duration: Pretest/ Perform Testing/Data Evaluation Days	Tests Done Together or Overlapping	Particular Testing or Timing Requirements
1. Clear Day Rec. Loop Evaluation.	I	3	10 days/2 days/10 days		
2. SGS and EPGS Operation	I	4	10/2/10		Hot tank charged
3. SGS/EPGS Characterization.	I	5	25/30/70		Hot tank charged
4. Operation With Simulated Clouds	I, II, III	10	30/40/80		Mirror reflectivity measured
5. Heliostat Patterns for Receiver Warm-up	I, II, III	7	10/130/170	6, 11	Various wind conditions
6. Receiver Efficiency Tests	II, IV	15	35/15/35	5, 11	Heliostats 98% avail., washed, aligned
7. Receiver Steady State Performance Map	II, IV	9	15/20/80	10, 11	Same as 6. Done a few days each season.
8. Thermal Losses Throughout Plant	II, IV	6	15/20/40	9, 12	Tests that affect operation not allowed
9. Parasitic Power Consumption.	II	8	30/10/40	8, 12, 13, 14	
10. Rec. Start. Follow. Rain	II	11	5/3/12	5, 7	After heavy rain
11. Rec. Drain During Wind	II	12	5/3/12	7	High wind
12. Optimized Receiver Loop Operations	III	16	60/45/70	8	Incorporate test 4 results
13. Overnight Thermal Conditioning	III	13	35/30/45	9, 12, 14	
14. Optimum Plant Operation	III, IV	17	40/20/50	12, 13	Incorporate tests 3, 12, 13 results
15. Power Production	IV	19	40/520/–	16	Results from test 14
16. Operation to Demo. Dispatchability	IV	18	10/6/10	15	Use results from test 3
17. Repeat Key Effic. and Perform. Tests	IV	14	15/30/50		Heliostats 98% avail., washed, aligned
18. Coupon Corrosion and Salt Chemistry	All	2 (initially)	5/–/20	21	Coupons installed during construction

Table 5-1. Sequencing of Tests, Duration, Overlapping Tests, and Testing or Timing Requirements (continued)

Test	Phase	Sequence	Duration: Pretest/ Perform Testing/Data Evaluation Days	Tests Done Together or Overlapping	Particular Testing or Timing Requirements
19. Storage Tank Thermal Stresses	Pre I, I	1	20/90/60		Instrumentation installed during construction
20. Extended Operational Tests	V	20	To be determined		Not part of scope of Solar Two
21. Post-Test Examination and Evaluation	V	21	30/40/80		After completion of power production phase

Table 5-2. Weather Requirement

	Weather Condition					
Test	**Sunny, Clear**	**Intermittent Partly Cloudy**	**Windy**	**Recent Rain**	**Independent of Weather**	**Comments**
1. Clear Day Receiver Loop Evaluation	x					
2. SGS and EPGS Operation	x					Entire plant needed
3. SGS/EPGS Characterization					x (partially)	Need hot salt
4. Operate With Simulated Clouds	x					
5. Heliostat Patterns for Receiver Warm-up	x		x			
6. Receiver Efficiency Tests	x		x			
7. Receiver Steady State Performance Map	x					
8. Thermal Losses Throughout Plant					x	Consistent weather
9. Parasitic Power Consumption					x	Consistent weather
10. Receiver Start up Following Rain	x			x		
11. Receiver Drain During Wind	x		x			
12. Optimized Receiver Loop Operations	x	x	x			
13. Overnight Thermal Conditioning					x	
14. Optimum Plant Operation	x	x	x	x		All weather cond.
15. Power Production	x	x	x	x		All weather cond.
16. Operation to Demo. Dispatchability	x					Need hot salt
17. Repeat Key Effic. and Perform. Tests	x		x			
18. Coupon Corrosion and Salt Chemistry					x	
19. Storage Tank Thermal Stresses	x (partially)				x (partially)	Done in initial fill
20. Extended Operational Tests						To be determined
21. Post-Test Examination and Evaluation					x (partially)	

Table 5-3. Time of Day and Seasonal Requirements

Test	Time of Day or Seasonal Requirement						
	Sunrise	Symmetric About Solar Noon	Various Times During Day	Night or Extended Cloudy Weather	Each Season	During One Season	No Time of Day or Seasonal Requirements
1. Clear Day Receiver Loop Evaluation							x (sunny weather)
2. SGS and EPGS Operation							x (sunny weather)
3. SGS/EPGS Characterization							x
4. Operate With Simulated Clouds						After March 21 Solstice	x (sunny weather)
5. Heliostat Patterns for Receiver Warm-up	x		x				
6. Receiver Efficiency Tests		x				x (summer)	
7. Receiver Steady State Performance Map			x		x		
8. Thermal Losses Throughout Plant				x			
9. Parasitic Power Consumption				x (partially)			
10. Receiver Start-up Following Rain							x (after rain)
11. Receiver Drain During Wind							x (at shutdown)
12. Optimized Receiver Loop Operations			x				
13. Overnight Thermal Conditioning				x		x	
14. Optimum Plant Operation			x				
15. Power Production			x				
16. Operation to Demo. Dispatchability			x				

Table 5-3. Time of Day and Seasonal Requirements (continued)

Test	Time of Day or Seasonal Requirement						
	Sunrise	Symmetric About Solar Noon	Various Times During Day	Night or Extended Cloudy Weather	Each Season	During One Season	No Time of Day or Seasonal Requirements
17. Repeat Key Effic. and Perform. Tests		x				x (summer)	
18. Coupon Corrosion and Salt Chemistry							x (samples removed at set time intervals)
19. Storage Tank Thermal Stresses							x
20. Extended Operational Tests							To be determined
21. Post-Test Examination and Evaluation							x

Table 5-4. Major Systems Availability Requirements and Special Instrumentation – All Tests Require the Master Control System to be Operational, Except Possibly Part of Test 19

Test	Major System or Special Instrumentation						
	Heliostat Field	Receiver Loop	Thermal Storage	SGS and EPGS	All Major Systems	Plant in Long-Term Hold	Special Instrumentation
1. Clear Day Receiver Loop Evaluation	x	x	x				Glint photometer
2. SGS and EPGS Operation					x		
3. SGS/EPGS Characterization			x	x	X (if no hot salt)		
4. Operate With Simulated Clouds	x	x	x				
5. Heliostat Patterns for Receiver Warm-up	x						IR camera
6. Receiver Efficiency Tests	x	x	x				IR camera
7. Receiver Steady State Performance Map	x	x	x				
8. Thermal Losses Throughout Plant					x		IR camera
9. Parasitic Power Consumption					x		Watt meter
10. Receiver Start up Following Rain	x	x	x				Rain gage
11. Receiver Drain During Wind		x	x				IR camera
12. Optimized Receiver Loop Operations	x	x	x				
13. Overnight Thermal Conditioning		x					
14. Optimum Plant Operation					x		
15. Power Production					x		

Table 5-4. Major Systems Availability Requirements and Special Instrumentation – All Tests Require the Master Control System to be Operational, Except Possibly Part of Test 19 (continued)

Test	Major System or Special Instrumentation						
	Heliostat Field	Receiver Loop	Thermal Storage	SGS and EPGS	All Major Systems	Plant in Long-Term Hold	Special Instrumentation
16. Operation to Demo. Dispatchability			x	x			
17. Repeat Key Effic. and Perform. Tests	x	x	x				IR camera
18. Coupon Corrosion and Salt Chemistry						x	Coupon test fixtures
19. Storage Tank Thermal Stresses			x (initial fill)				Strain gage, DAS
20. Extended Operational Tests					TBD		
21. Post-Test Examination and Evaluation					TBD		

6.0 Data Collection and Processing

6a. Permanent Plant Data Acquisition System (DAS)

Solar Two will have a data acquisition system which will record data from a variety of plant instrumentation. The data acquisition system will store the data on disk and be able to replay the data or archive the data to a transportable storage media.

A system hardware schematic is shown in MCS System Block Diagram, Drawing JO-101. The data acquisition software will share the Host Computer with the Operating Control System and Heliostat Array Control software. Data will arrive from the following sources:

1. Distributed Process Controller System
2. Programmable Logic Controllers
3. Heliostat Array Controller Software
4. Heat Tracing Controller.

The data acquisition system will record data on local hard disk and will archive data to DAT tape cartridges. Data may be played back in the Evaluation Room on two color monitors and two black and white text displays. A printer will provide hard copies of data and plots.

Installed Data Acquisition Software

The data acquisition software will handle communication with all of the systems which supply it data. The data acquisition software will store the data it receives and be able to archive the data to tape cartridge in engineering units. The data acquisition software will support display of data as it is received or at a later time in playback mode. The data acquisition system will provide means to manage its configuration so that it may be adapted as needs change.

Data Acquisition System Data

The data acquisition system will acquire and store the data listed in the Appendix. A summary of the number of measurements of each type is shown in Table 6-1. The source of the data can limit the rate at which data can be acquired. The nominal sample rates associated with each data source are shown below:

- **DPCS** – 1 sample/10 seconds maximum, 1 sample/minute normal
- **PLC** – 1 sample/10 seconds normal, 1 sample/second on 60 channels
- **HAC** – 1 sample/2 minutes
- **Heat Tracing Controller** – updates every minute.

Table 6-1. Summary of Data Types

Data Type	No. of Measurements
Electric Power Consumption	16
Flowrate	8
Flux	24
Heat Tracing	290

Heliostat	4
Level	8
Meteorological	15
Miscellaneous	5
Photometer	8
Pressure	16
Speed	5
Temperature	337
Valve Position	79
Total	815

The heliostat data is provided by the HAC in four formats. Each format is a string of ASCII characters which must be decoded to extract the required information. The data acquisition system will not decode the formats; decoding must be done by the evaluation software as defined in this chapter.

6b. Test and Evaluation Team Office Test Equipment

Hardware

The Test and Evaluation Team will need office and computing equipment. A candidate equipment inventory is:

1. IBM PC 486 or better computers (clones ok). Each computer to have two 500 Mbyte hard disks as a minimum. Modems shall be installed and CD ROM reader.
2. FAX.
3. Scanner; to be attached to one IBM PC.
4. 2 Laser printers, 1 for the workstations, the other for the IBM PC's. Each printer capable of printing 8.5x11 and 11x17 size paper.
5. 3 DAT tape cartridge device identical to that used by the data acquisition system and connected to the workstations.
6. 4 offices with two desks and chairs each. A telephone for each desk.
7. Photocopier or access to a photocopier provided by others.
8. Conference room with a large table and chairs for 10 people.
9. Basic office supplies of pens, pencils, stationary, staplers, paper clips, etc.

Data Reduction and Analysis Software

Software is to be purchased or developed for use by the on-site test and evaluation team.

1. Data reformatting software – reads data in the Data Acquisition System formats and converts the data to a uniform format for use by data reduction software.
2. Data verification software – automated software which verifies that the data acquired is good. Identifies and prints out the tag ID's of bad data for maintenance action. With user ok, marks bad data as bad.

3. Plant energy calculations software – computes the daily, monthly, and yearly energies and efficiencies called out in Test 14 and 15.
4. Outage Impact software – uses the data from the operator provided outage logs and the plant data to compute the energy lost due to outages.
5. Data Fusion software – software (may be multiple programs) which allows the user to maintain a database of reference data from multiple sources and data types.
6. MatLab.
7. Microsoft Word for each IBM PC.
8. Microsoft Excel for each IBM PC.
9. Drafting/drawing program for each IBM PC.
10. Optical character reader software for the IBM PC connected to scanner.
11. Automatic backup software.
12. Terminal emulator software.
13. Higher level language compiler (FORTRAN or C) if necessary.

6c. Data Archiving

Data will be written to disk as it is acquired. Data will be stored on two disks simultaneously with one disk containing data redundant to the other.

Data will be archived to DAT for long term storage. A minimum of two DAT tapes will be written in case one tape should be accidentally destroyed. Each tape will be labeled unambiguously.

7.0 Deliverables

The T&E team will be responsible for preparing three categories of reports for documenting the performance and operation of Solar Two. Those three categories cover the documentation of the test results, the presentation of the evaluations and the extrapolation of findings to future plants. The three categories are described in more detail in the following sections.

The objectives of the T&E Plan reports are as follows:

- Test results are provided in a timely manner to the technical staffs of the Participants so that they can be reviewed and the test repeated or modified, if required, in a timely manner.
- A record of Solar Two's performance can be disseminated to the Participants to form a database for future projects and individual studies.
- Information will be provided for related projects such as the Commercialization Plan and solar-hybrid studies.

The Operations and Maintenance (O&M) Contractor has separate requirements for reports and other documentation that are described in the Statement of Work to the contract, which also references the appropriate section of the T&E Plan.

7a. Test Results

This is the most detailed and least formal of the report categories. The reports will describe the tests performed, the test procedures, data reduction methodology, and findings based on the results. The predicted values will be listed, comparisons made with results and significant departures from predictions will be discussed. Unexpected or unusual events that occurred during the tests will be described. Equipment failures will be noted. Each test description contains a section of Deliverables which will be addressed in the test report.

Because some of the tests in the T&E Plan are for familiarization or do not warrant a separate report, reports can be combined as follows. Tests 3 though 9, 12 and 13 will have individual reports of their test results. Tests 1 and 2 will be reported with Test 3, Tests 10 and 11 will be reported with Test 7. These reports will be informally produced and issued soon after the tests are completed, or at a convenient intermediate point in a long test sequence so that reviewers can provide comments and feedback on the remainder of the individual tests. In the latter cases, the reports will be revised so that the final revision contains all the information on the test.

7b. Evaluation Reports

The second category of report will be used as follows:

- An evaluation report that documents the highlights and completion of the Test and Evaluation Plan up to Test 14.
- Presentation of the results and conclusions of Test 15 and 16 for the first year of power production, and a summary report combining the data from both years. Key efficiency data from Test 17 could be included.

7c. Projections for Solar 100

This category covers documentation associated with the Solar Two Project that extends the utilization of the project database in a series of scale-up and lessons-learned applications. These reports will be beyond the scope of the T&E plan. The following is provided as an example of a report in this category.

Report Title: Application of Solar Two Results to Solar 100 Project

Report Scope:

- Scale -up of baseline Solar Two design to Solar 100, where appropriate.
- Application of Solar Two Lessons-Learned to Solar 100 design.
- Revised Solar 100 design.
- Cost and performance prediction based on Solar 100 revised design (requires SOLERGY output based on Solar Two results).
- Risk assessment of revised Solar 100 design.

7d. Nitrate Salt Receiver Design Guide

Nitrate Salt Central Receiver Design Guide will be updated to capture results of Solar Two Start-up Test and Evaluation progress and experiences, and Lessons Learned by Test and Evaluation Program.

8.0 Reference Documents

Dwg. No.	Title
PO-001	GENERAL ARRANGEMENT CORE AREA PLAN BELOW EL. 150′-0″
PO-005	GENERAL ARRANGEMENT CORE AREA SECTIONS A-A AND B-B
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Dwg. No.	Title
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3YD-CS-001	SYSTEM DESCRIPTION FOR COLLECTOR SYSTEM
3YD-DG-001	DESIGN GUIDE FOR COMMERCIAL CENTRAL PROJECTS

Dwg. No.	Title
3YD-EPGS-001	SYSTEM DESCRIPTION FOR ELECTRICAL POWER GENERATION SYSTEM
3YD-RS-001	SYSTEM DESCRIPTION FOR RECEIVER SYSTEM
3YD-SGS-001	SYSTEM DESCRIPTION FOR STEAM GENERATOR SYSTEM
3YD-TSS-001	SYSTEM DESCRIPTION FOR THERMAL STORAGE SYSTEM

SOLAR TWO PROJECT

Test and Evaluation Plan
Volume 2

No.	DATE	REVISIONS	BY	CH'K	APPR.
0	5/11/95	Issued for Implementation	TAC-Subcommittee		
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ORIGIN Bechtel Corp.	**SOLAR TWO PROJECT** Daggett, California Test and Evaluation Plan	**Job No. 21948** Document Number: 3PS-G-003	Rev.: 0

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1.0 Test Plans

1.1 Clear Day Receiver Loop Operation

Test No.: 1 Clear Day Receiver Loop Operation

Description: Exercise the manual and automatic steady-state and transitional operation of the receiver under clear sky conditions. Measure receiver glint.

Objectives:

1. Confirm operation of the receiver loop in all operating states.
2. Confirm the adequacy of the operating procedures and automated sequences.
3. Thoroughly familiarize the Test and Evaluation team with the receiver loop operation and data collection.
4. Determine the safety of viewing the receiver with the naked eye from the plant boundary.

Prerequisites:

Preanalysis – None

Verify Calibration – None

Plant Operating Status – Both Cold Salt Pumps functional
All valves verified controllable from control room
All pumps verified controllable from control room
All instrumentation verified operational
Heliostat field able to operate the receiver

Weather – Solar radiation greater than 400 W/m^2
No clouds which can cover the sun

Other – None

Precautions:

Do not perform operations or trips that were not qualified during the Start-up and Acceptance phase. Confirm that all salt piping and components are above 550 °F prior to fill.

Test Sequence:

Receiver Operations

1. Operate the receiver loop manually in all operating states and through all transitions under clear day conditions.
2. Operate the receiver loop using the automated transition sequences.
3. Exercise receiver trips and set-backs during various states and transitions for familiarization with all alarms and automated shutdown procedures.

Glint

4. Measure receiver glint with glint meter from perimeter road on the south side, fence line at north, south, east and west sides, and nearest public road.

Data Requirements:

Key Instruments	–	Record the following instruments with the DAS: TI5104 – east inlet salt temperature TI5166A and B – east outlet salt temperatures TI5304 – west inlet salt temperature TI5366A and B – west outlet salt temperatures FI5102 – east salt flowrate FI5302 – west salt flowrate LI5002A and B – receiver inlet tank level PI5003 – receiver inlet tank pressure LI5022 – receiver outlet tank high level LI5023 – receiver outlet tank level
Duration	–	Record key instruments for duration of testing
Frequency	–	Record key instruments at 1 sample per 10 seconds

Data Reduction:

Data reduction is limited to pass/fail type criteria; either the control state or transition works or it doesn't. The criteria need to be established in terms of tolerances in the control variable steady-state value or percent of overshoot/undershoot of the control variable.

Deliverables:

Familiarization of operators and Test and Evaluation team with Solar Two operation

Glint Data

Acceptance Criteria:

The Test and Evaluation Team is familiar with operations in all states, transitions, setbacks, and trips.

Resources Required:

Pretest	–	Test engineer and operator to prepare key instrument recording and displays for DAS
Test	–	Test engineer and regular operation staff
Posttest	–	Test engineer, DAS playback, data processing equipment per Test and Evaluation Plan

1.2 Steam Generator Operation and Electric Power Generation

Test No.: 2 Steam Generator Operation and Electric Power Generation

Description: Exercise the manual and automatic steady-state and transitional operation of the Steam Generating System and Electrical Power Generating System.

Objectives:

5. Confirm operation of the steam generator and EPGS systems.
6. Confirm steam generator design heat balance.
7. Confirm operation using automated sequences.
8. Qualify steam generator/EPGS systems for heat rejection throughout the remainder of receiver loop testing (tests 3 through 15).
9. Familiarize test team with all operations and data collection.

Prerequisites:

Preanalysis	–	None
Verify Calibration	–	None
Plant Operating Status	–	Both Hot Salt Pumps and salt mixer pump functional All valves verified controllable from control room All pumps verified controllable from control room All instrumentation verified operational
Weather	–	Not applicable
Other	–	None

Precautions:

Do not perform operations or trips that were not qualified during the Start-up and Acceptance phase.

Test Sequence:

1. Start-up and operate the steam generator manually, bypass the turbine for heat rejection.
2. Repeat steam generator start-up and operation using the automated sequences.
3. Start-up and operate the turbine generator. Synchronize to the grid.
4. Record plant data during these operations.
5. Sequence test 2 with test 1 so that thermal storage is charged in test 1 and discharged in test 2.
6. Exercise the Steam Generation System and turbine trips and setbacks during various states and transitions for familiarization with all alarms and automated shutdown procedures.

Data Requirements:

Key Instruments	–	Record the following instruments with the DAS: TE5775 – superheater inlet salt temperature TE5757 – boiler inlet salt temperature TE5763 – preheater outlet salt temperature FI5776 – preheater outlet salt flowrate FI5718 – salt mixer pump flowrate TI5753 – superheater outlet steam temperature PI5756 – superheater outlet steam pressure LI5670 – boiler water level TI5769 – preheater inlet water temperature
Duration	–	Record key instruments for duration of testing
Frequency	–	Record key instruments at 1 sample per 10 seconds

Data Reduction:

Data reduction is limited to pass/fail type criteria; either the control state or transition works or it doesn't. The criteria need to be established in terms of tolerances in the control variable steady-state value or percent of overshoot/undershoot of the control variable.

Deliverables:

Familiarization of operators and Test and Evaluation team with Solar Two operation

Acceptance Criteria:

Test and Evaluation team familiar with operations in all states, transitions, setbacks, and trips.

Resources Required:

Pretest	–	Test engineer and operator to prepare key instrument recording and displays for DAS
Test	–	Test engineer and regular operation staff
Posttest	–	Test engineer, DAS playback, data processing equipment per Test and Evaluation Plan

1.3 Steam Generator/EPGS Characterization

Test No.: 3 **Steam Generator/EPGS Characterization**

Description: Operate the Steam Generator and Electric Power Generation Systems together over their design range of operation gathering transient and steady-state performance data. Operate the entire plant (combined receiver, SGS, and EPGS).

Objectives:

1. Confirm full plant's range of operation: turbine-generator start-up/shutdown, steady-state operation, and overnight operation.
2. Measure power conversion efficiency at rated (100 percent), 75 percent, and 50 percent power, and hot salt temperatures less than 1,050 °F.
3. Measure steam generator and turbine-generator start-up and cooldown times and salt flowrates.

Prerequisites:

Preanalysis	–	Heat exchanger performance predictions for steam generator from manufacturer. Turbine performance predictions for turbine/generator from manufacturer. System (SGS coupled to turbine-generator) performance predictions by Test and Evaluation Team.
Verify Calibration	–	TE5775 – superheater inlet salt temperature TE5757 – boiler inlet salt temperature TE5763 – preheater outlet salt temperature FT5776 – preheater outlet salt flowrate FT5718 – salt mixer pump flowrate TE5744 – cold salt sump temperature TE5753 – superheater outlet steam temperature PT5756 – superheater outlet steam pressure LT5670 – boiler water level TE5769 – preheater inlet water temperature PT5767 – preheater inlet water pressure JT5100 – gross electric power JT5102A – net electric power
Plant Operating Status	–	Receiver operated to provide hot salt for this test. SGS and EPGS on-line, turbine synchronized to grid.
Weather	–	Clear sunny days
Other	–	None

Precautions:

Monitor the preheater temperature to avoid salt freezing.

Test Sequence:

1. Operate receiver, SGS, EPGS together. First start the receiver and begin fill of the hot salt tank. Once the hot salt tank is 30 percent full, start the SGS, then warm and roll the turbine, then synchronize the generator to the grid. Operate at rated output for 30 minutes.
2. Place SGS/EPGS in each steady-state as defined in the table below for 15 minutes. Steady-state is achieved when all table values vary less than 3 percent from their set point. Tests may be conducted over several days.

Test No.	Hot Salt Temp. TI5755 °F	Salt Outlet Flow FI5776 klbm/hr	Steam Pressure PIX926 psia	Steam Temp. TI5753 °F	Steam Temp. TI5788 °F
3.1	1,050	728	1,465	1,000	950
3.2	1,050	546	1,465	1,000	950
3.3	1,050	364	1,465	1,000	950
3.4	950	728	1,465*	900	900
3.5	950	546	1,465*	900	900
3.6	950	364	1,465*	900	900
3.7	850	728	1,465*	800	800
3.8	850	546	1,465*	800	800
3.9	850	364	1,465*	800	800
* Or maximum pressure possible that meets minimum superheat requirement.					

Data Requirements:

Key Instruments – None

Duration – Not applicable

Frequency – Not applicable

Data Reduction:

1. At conditions of steady-state, compute the efficiency of the steam generator for each condition from the table above as follows:

$$\text{Efficiency}_{\text{steam gen.}} = \frac{\sum P_{\text{turbine}_n} \Delta t_n}{\sum P_{\text{stm gen}_n} \Delta t_n}$$

where the calculations for $P_{\text{stm gen}_n}$ and are shown in later in this section.

2. Tabulate the power sent to the steam generator, $P_{\text{stm gen}_n}$, power to turbine, P_{turbine_n}, gross electric power, JI5100, and net electric power, JI5102A, for all conditions of the above table.

Power Sent to the Steam Generator

$$\begin{aligned} P_{\text{stm gen}_n} &= (FI5776_n - FI5718_n) * cp(TI5777_n) * TI5777_n \\ &+ FI5718 * cp(TI5050_n) TI5050_n - FI5776_n * cp(TI5763_n) * TI5763_n \end{aligned}$$

where:

$P_{stm\ gen_n}$	=	power sent to the steam generator, MWt.
FI	=	salt mass flowrate, lbm/sec. The steam generator will receive salt from the hot tank and the cold tank. The salt from the cold tank is used to reduce the hot salt temperature in an attemperation mixer if the hot salt is too hot. Flowmeter data, pressure data, and pump speeds will be to provide the most accurate estimate of salt flowrates possible.
cp	=	specific heat, B/lbm-°F. The specific heat of the salt will be computed by a subroutine using temperature curve fits.
TI	=	temperature, °F.
n	=	counter for delineating one data sample from another.

Power to Turbine

$$P_{turbine_n} = FI5785_n * (h_{s1_n} - h_{w_n})$$

where:

$P_{turbine_n}$	=	power to turbine, MWt.
$FI5785_n$	=	steam mass flowrate, lbm/sec.
h_{s1_n}	=	enthalpy of steam leaving superheater, B/lbm = $hpt(TI5753_n, PI5756_n)$.
h_{w_n}	=	enthalpy of feedwater, B/lbm = $hpt(TI5769_n, PI5767_n)$.
hpt	=	enthalpy calculation function. Computer subroutines will compute the enthalpy as a function of temperature and pressure.
n	=	counter for delineating one data sample from another.

3. Start-up Thermal and Electrical Energy. For each steam generator start-up, compute the start-up thermal and electrical energy per the equation below.

$$E^{thermal}_{Stm\ Gen\ Startup} = \sum \frac{P_{stm\ gen_n} + P_{stm\ gen_{n-1}}}{2} (t_n - t_{n-1})$$

$$E^{electric}_{Stm.\ Gen.\ Startup} = \sum \left[\frac{\begin{array}{c}(P_{hot\ salt\ pump} + P_{stm.\ gen.\ HT} + P_{att.\ pump} + P_{recirc.\ pump} + P_{recirc.\ htr.})_n + \\ (P_{hot\ salt\ pump} + P_{stm.\ gen.\ HT} + P_{att.\ pump} + P_{recirc.\ pump} + P_{recirc.\ htr.})_{n-1}\end{array}}{2} \right] (t_n - t_{n-1})$$

where:

$E^{thermal}_{Stm\ Gen\ Startup}$	=	thermal energy consumed to bring the generator on-line.

$E^{electric}_{Stm.\,Gen.\,Startup}$	=	electrical energy consumed to bring the generator on-line.
$P_{stm\ gen_n}$	=	power sent to the steam generator, MWt.
$P_{turbine_n}$	=	power to turbine, MWt.
$P_{hot\ salt\ pump}$	=	hot salt pump electric power, MWe.
$P_{stm.\ gen.\ HT}$	=	steam generator heat tracing power, MWe.
$P_{att.\ pump}$	=	fill and attemperator pump power, MWe.
$P_{recirc.\ pump}$	=	recirculation pump power, MWe.
$P_{recirc.\ htr.}$	=	recirculation electric heater power, MWe.
t	=	time at which data was taken, hours.
n	=	counter for delineating one data sample from another.

This calculation is to occur from the initiation of steam generator start-up until rated steam conditions are reached and the turbine is synchronized with the grid.

4. **Overnight Thermal Conditioning** – The baseline overnight thermal conditioning (short-term hold) method for the Steam Generation System is 'pump bumping' with some heat tracing on small diameter piping and possible operation of the recirculation system about the preheater. Since the Steam Generator also provides auxiliary steam during a short-term hold, the energy for producing auxiliary steam is included.

$$E^{thermal}_{Short\text{-}term\ Hold} = \sum \frac{P_{stm\ gen_n} + P_{stm\ gen_{n-1}}}{2}(t_n - t_{n-1})$$

$$E^{electric}_{Short-term\ hold} = \sum \left[\frac{\begin{array}{c}(P_{hot\ salt\ pump} + P_{stm.\ gen.\ HT} + P_{att.\ pump} + P_{recirc.\ pump} + P_{recirc.\ htr.})_n + \\ (P_{hot\ salt\ pump} + P_{stm.\ gen.\ HT} + P_{att.\ pump} + P_{recirc.\ pump} + P_{recirc.\ htr.})_{n-1}\end{array}}{2} \right](t_n - t_{n-1})$$

5. Plot the power production and parasitic power over a 24-hour period.

Deliverables:

Performance tables and plots for steam generator and turbine-generator.

Departures from prediction and reasons why.

Acceptance Criteria:

Definition of steam generator and turbine-generator performance adequate for plant performance modeling.

Resources Required:

Pretest	–	Test engineer and instrument technician for instrument calibration
Test	–	Test engineer and regular operations staff
Posttest	–	Test engineer, data processing equipment per Test and Evaluation Plan

1.4 Operation With Simulated Clouds

Test No.: 4 Operation With Simulated Clouds

Description: Phase I and II — Vary the flux on the receiver by removing/adding selected groups of heliostats. Obtain data on the receiver and control system response.

This test will have been conducted during the start-up phase. Results will be extended here to cover a larger range of variables.

Phase III — Control loop tuning will allow operation through all transient conditions with limited outlet salt temperature setbacks.

The two receiver loops will be evaluated through these transients and the adequacy of the single crossover will be assessed.

Data from this test and natural cloud transients obtained in subsequent operation and testing will be used in the optimization of the receiver loop, Test 12.

Objectives:

Phase I and II

1. Determine the transient response characteristics of receiver loop operation.

Phase III

1. Qualify system for operation through all natural cloud transients with a minimum degradation of the collected energy.
2. Determine the control loop gains and procedures required to operate safely and efficiently through all transients, whether caused by clouds or other reasons.

Prerequisites:

Preanalysis – Predictions for the response of the receiver loop operation to step changes in solar radiation are required from the receiver manufacturer.

Verify Calibration – TE5104 – east inlet salt temperature
TE5166A and B – east outlet salt temperatures
TE5304 – west inlet salt temperature
TE5366A and B – west outlet salt temperatures
FT5102 – east salt flowrate
FT5302 – west salt flowrate
LT5002A and B – receiver inlet tank level
PT5003 – receiver inlet tank pressure
LT5022 – receiver outlet tank high level
LT5023 – receiver outlet tank level
ST5051 – speed indicator on pump P-250A

ST5053 – speed indicator on pump P-250B
LT5018 – level gage on cold salt sump
ZT5022 – downcomer drag valve position
ZT5023 – backup downcomer drag valve position
YI5183 – receiver photometer
YI5184 – receiver photometer
YI5185 – receiver photometer
YI5186 – receiver photometer
YI5383 – receiver photometer
YI5384 – receiver photometer
YI5385 – receiver photometer
YI5386 – receiver photometer
cleaned and adjusted daily
AI9010 – control room roof normal incident pyrheliometer
AI9011 – control room roof normal incident pyrheliometer

Plant Operating Status – Plant start-up complete. Test 1 completed.

Weather – Clear sky conditions

Other – None

Precautions:

Steps back to the higher power level should be assessed for potential damage to receiver and impact on the receiver equipment warranty. Limitations are max. allowable salt for temperature, allowable rate of change of metal temperature, and max. allowable front surface metal temperature.

Test Sequence:

2. Place the receiver in the steady-state initial conditions indicated in the table below. Once steady-state is achieved (receiver outlet temperature continuously within tolerance for 10 minutes minimum), initiate fast scan capture of key instrumentation data, and reduce the power level of the heliostat field as indicated in the table. Wait until steady-state is achieved. Once steady-state has been reached, command all heliostats removed to once again track the receiver. When steady state is achieved once again, halt fast scan capture of key instrumentation data.

		Receiver Outlet Temperature				
Test No.	Time of Day	East TI5166A °F	West TI5366A °F	Mixed TI5024 °F	Percent Power at Beginning of Step	Percent Power at End of Step
4.1						
4.2						
4.3						
4.4						
4.5						

Test No.	Time of Day	Receiver Outlet Temperature East TI5166A °F	West TI5366A °F	Mixed TI5024 °F	Percent Power at Beginning of Step	Percent Power at End of Step
4.6						
4.7						
4.8						
4.9						

Data Requirements:

Key Instruments – TI5104 – east inlet salt temperature
TI5166A and B – east outlet salt temperatures
TI5304 – west inlet salt temperature
TI5366A and B – west outlet salt temperatures
FI5102 – east salt flowrate
FI5302 – west salt flowrate
LI5002A and B – receiver inlet tank level
PI5003 – receiver inlet tank pressure
LI5022 – receiver outlet tank high level
LI5023 – receiver outlet tank level
TI5024 – receiver outlet tank outlet temperature
SI5051 – speed indicator on pump P-250A
SI5053 – speed indicator on pump P-250B
LI5018 – level gage on cold salt sump
ZI5022 – downcomer drag valve position
ZI5023 – backup downcomer drag valve position
YI5183 – receiver photometer
YI5184 – receiver photometer
YI5185 – receiver photometer
YI5186 – receiver photometer
YI5383 – receiver photometer
YI5384 – receiver photometer
YI5385 – receiver photometer
YI5386 – receiver photometer
TI5122A and B – Panel E1 center thermocouples
TI5123A and B – Panel E2 center thermocouples
TI5124A and B – Panel E3 center thermocouples
TI5125A and B – Panel E4 center thermocouples
TI5126A and B – Panel E5 center thermocouples
TI5127A and B – Panel E6 center thermocouples
TI5128A and B – Panel E7 center thermocouples
TI5129A and B – Panel E8 center thermocouples
TI5130A and B – Panel E9 center thermocouples
TI5131A and B – Panel E10 center thermocouples
TI5132A and B – Panel E11 center thermocouples

TI5133A and B – Panel E12 center thermocouples
TI5322A and B – Panel W1 center thermocouples
TI5323A and B – Panel W2 center thermocouples
TI5324A and B – Panel W3 center thermocouples
TI5325A and B – Panel W4 center thermocouples
TI5326A and B – Panel W5 center thermocouples
TI5327A and B – Panel W6 center thermocouples
TI5328A and B – Panel W7 center thermocouples
TI5329A and B – Panel W8 center thermocouples
TI5330A and B – Panel W9 center thermocouples
TI5331A and B – Panel W10 center thermocouples
TI5332A and B – Panel W11 center thermocouples
TI5333A and B – Panel W12 center thermocouples
AI9010 – control room roof normal incident pyrheliometer
AI9011 – control room roof normal incident pyrheliometer

IR Camera – Station IR camera at field coordinates shown below. Observe the locations called out in the table below at the magnification shown.

	IR Cam. Location	Receiver Location	Magnification
1.			
2.			
3.			
4.			

Duration – Individual tests as called out in test procedure. Overall test length is anticipated to be 15 days containing 36 good transients.

Frequency – All key instruments except IR camera: 1 sample per 10 seconds

IR Camera – Record image on videotape for post processing

Data Reduction:

1. Compare recorded data to prediction.
2. Determine cause of differences between prediction and recorded data.
3. Determine changes to receiver control system parameters for improving performance.
4. Retest as necessary and repeat steps 1 through 3.

Deliverables:

Phase II

1. Plots of the transient response of the receiver (overall and individual loops) to insolation transients.
2. Adequacy of single receiver panel crossover.
3. Limitations, if any, caused by rate of change of metal temperature on receiver operation.
4. Identification of reasons for any operating constraints (lessons learned).

Phase III
1. Receiver loop tuning parameters.
2. Procedures for operation through transients including any operating constraints.

Acceptance Criteria:

Phase I Test and Evaluation Team familiar with operation during receiver transients.

Phase II Fully characterize the receiver loop during insolation transients.

Phase III
a. Optimize the control system for maximum power production while protecting the receiver.
b. Identify design changes which could improve power production.

Resources Required:

Pre-Test – One test engineer and one operator. Tasks are:
a. Program DAS for recording and displaying data.
b. Prepare heliostat control file for automated sequencing of heliostat commands in order to perform tests.
c. Review any test specific operating procedures.

Test – Test engineer and regular operations staff
Test engineer to operate IR camera

Post-Test – One test engineer. Tasks are:
a. Compare actual response to predicted.
b. Revise model and prepare changes to control programming.
c. Record lessons learned.

1.5 Heliostat Patterns for Receiver Warm-Up

Test No.: 5 Heliostat Patterns for Receiver Warm-Up

Description: Obtain temperature versus time data for the warm up the receiver to start-up temperatures using prescribed heliostat aiming patterns under a variety of ambient wind and temperature conditions and time of day.

This test will have been conducted during the start-up phase. It is assumed that warm-up patterns for different times of day and different days of the year were entered as part of the automated start-up program. Results will be extended here to cover a larger range of conditions and to try to reduce the warm-up time (if this is important). Data from subsequent tests will be included for this evaluation in order to cover different wind conditions and seasons.

Objectives:

Phase I – Familiarize the Test and Evaluation Team with heliostat warm-up patterns.

Phase II – Identify heliostat patterns for receiver warm-up under all wind conditions and time of day. (Data will be extended to cover time of year.)

Phase III – Optimize this phase of plant start-up.

Prerequisites:

Preanalysis – Calculations/predictions for receiver warm-up from supplier of receiver warm-up software.

Verify Calibration – Clean and adjust normal incident pyrheliometers daily.

Plant Operating Status – Plant start-up complete. Initial warm-up patterns installed and checked.

Weather – Clear sky conditions.

Other – None

Precautions:

Operate within constraints of maximum temperature and maximum temperature ramp rates.

Test Sequence:

Phase I – Warm up the receiver to start-up temperatures per plant requirements using prescribed heliostat aiming patterns from computer simulations.

Phase II – Repeat warm-up tests for various wind speed conditions and at different times of day. Data should be taken for the conditions called out in the table below.

Test No.	Time of Day	Wind Speed
5.1		
5.2		
5.3		
5.4		
5.5		
5.6		
5.7		
5.8		
5.9		
5.10		

Phase III – Modify heliostat aiming patterns to achieve optimal warm-up (minimum time and minimum temperature variation over the receiver).

Note: Some of these tests will need to be interspersed with other tests in order to obtain the desired wind conditions.

Data Requirements:

Key Instruments – TI5122A and B – Panel E1 center thermocouples
TI5123A and B – Panel E2 center thermocouples
TI5124A and B – Panel E3 center thermocouples
TI5125A and B – Panel E4 center thermocouples
TI5126A and B – Panel E5 center thermocouples
TI5127A and B – Panel E6 center thermocouples
TI5128A and B – Panel E7 center thermocouples
TI5129A and B – Panel E8 center thermocouples
TI5130A and B – Panel E9 center thermocouples
TI5131A and B – Panel E10 center thermocouples
TI5132A and B – Panel E11 center thermocouples
TI5133A and B – Panel E12 center thermocouples
TI5322A and B – Panel W1 center thermocouples
TI5323A and B – Panel W2 center thermocouples
TI5324A and B – Panel W3 center thermocouples
TI5325A and B – Panel W4 center thermocouples
TI5326A and B – Panel W5 center thermocouples
TI5327A and B – Panel W6 center thermocouples
TI5328A and B – Panel W7 center thermocouples
TI5329A and B – Panel W8 center thermocouples
TI5330A and B – Panel W9 center thermocouples
TI5331A and B – Panel W10 center thermocouples
TI5332A and B – Panel W11 center thermocouples
TI5333A and B – Panel W12 center thermocouples

Backside thermocouples TI5195 through TI5266
Backside thermocouples TI5395 through TI5366
Photometers YI5183 through YI5186
Photometers YI5383 through YI5386
Record dynamic aimpoint and heliostat warm-up pattern.
Record heliostat field status.
Record the time from test start until ready to flow salt in the receiver.
Record maximum and minimum temperature of receiver during test.

IR Camera – Station at field coordinates X, Y. Observe the locations called out in the sample input table (***Table)*** at the magnification shown.

	Receiver Location	Magnification
1.		
2.		
3.		
4.		

Duration – Overall test length is anticipated to be 10 days covering 15 receiver warm-ups plus at least 10 warm-ups measured in later tests. Five test days will be shared with receiver efficiency test runs (test 6).

Frequency – All key instruments except IR camera: 1 sample per 10 seconds

IR camera – Record image on videotape for post processing.

Data Reduction:

1. Compare recorded data to prediction.
2. Determine cause of differences between prediction and recorded data.
3. Implement changes to algorithm which determines heliostat warm-up patterns to improve receiver warm-up.
4. Retest as necessary and repeat steps 1 through 3.

Deliverables:

Phase I 1. Familiarization of the Test and Evaluation Team.

Phase II 1. Start-up time as a function of the variables tested.

Phase III 1. Heliostat warm-up patterns including the impact of the wind direction and speed.
2. Revision to the automated start-up program.

Acceptance Criteria:

Phase I 1. Test and Evaluation Team familiar with heliostat warm-up.

Phase II 1. Fully characterize receiver warm-up with heliostats process.

Phase III 1. Optimize the heliostat warm-up process to maximize annual power production.

2. Identify design changes which could improve power production.

Resources Required:

Pre-Test – One test engineer full time for 1 month. Tasks are:

a. Prepare predicted responses for comparison with actual data
b. Determine whether a test may risk damage to the receiver.

One test engineer and one operator. Tasks are:

a. Program DAS for recording and displaying data
b. Review any test specific operating procedures.

Test – Two test engineers and regular operations staff.

a. One DAS screen to made available to test engineer for review of heliostat temperature data
b. Test engineer to operate IR camera.

Post-Test – One test engineer. Tasks are:

a. Compare actual response to predicted
b. Revise model and prepare changes to warm-up heliostat file
c. Record lessons learned.

1.6 Receiver Efficiency Tests

Test No.: 6 **Receiver Efficiency Tests**

Description: Measure the receiver's efficiency as accurately as possible using two methods: (1) complementary heliostat groups (power-on method), and (2) receiver cooldown (power-off method).

The following two temperatures only should be used for the power-off tests: 550 °F and 700 °F.

The power-on tests should be conducted with two sets of complementary heliostats such that one set (both groups) contains approximately the entire field and the other set has about half of this radiation.

Objectives:

Receiver efficiency map as a function of operating temperature with some correlation to wind speed.

Prerequisites:

Preanalysis	–	Prediction of receiver efficiency from receiver manufacturer
Calibration	–	TE5104 – east inlet salt temperature TE5166A and B – east outlet salt temperatures TE5304 – west inlet salt temperature TE5366A and B – west outlet salt temperatures FT5102 – east salt flowrate FT5302 – west salt flowrate Measure heliostat field cleanliness every 3 days during test period. If precipitation or a dust storm occurs during the test period, remeasure field cleanliness directly after. Measure receiver absorptivity within 3 months of test per receiver absorptivity measurement plan.
Plant Operating Status	–	Heliostat field at 90 percent or better availability with heliostat outages randomly scattered throughout the field. Heliostat field alignment verified by BCS within the last 6 months. Receiver system controls able to tolerate a 50 percent of max. power level change and damp response of receiver within 15 minutes. Turn off receiver loop heat tracing for power-off testing.
Weather	–	Clear day. Peak insolation predicted to be 800 W/m^2 or more. Wind below 5 mph for one set of tests, wind between 10 and 20 mph for second set of tests. For Phase IV testing (during power production), the test day weather should be similar to one of the Phase II weather conditions.
Other	–	None

Precautions:

1. Limit rate at which heliostats can be placed back on the receiver so as not to exceed receiver control capability.
2. Care must be exercised when performing power-off testing at 700 °F not to exceed the minimum level in the cold tank so that after testing, cold salt may be added to lower the salt temperature. This is due to receiver inlet temperature limitations during high insolation periods.
3. Assess tests performed during windy conditions to insure a high enough salt flow to preclude freezing in the receiver.

Test Sequence:

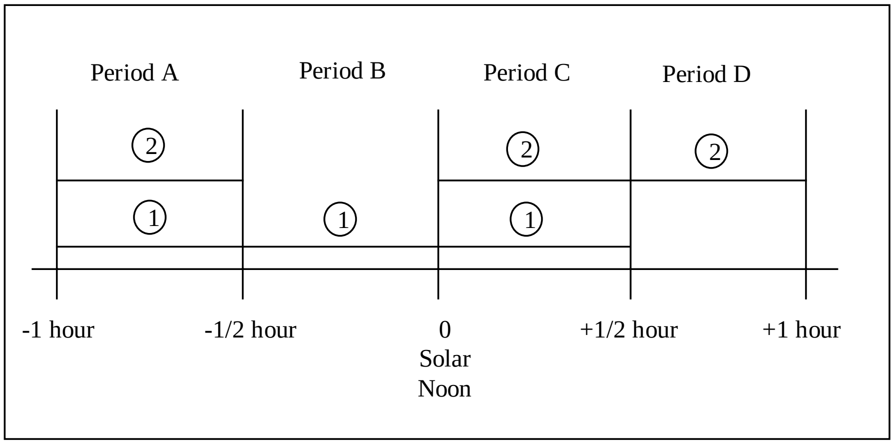
Power Off Testing

1. **Testing at 550 °F** – Flow cold salt at 550 °F ±20 °F through the receiver with no heliostats tracking the receiver. Cold salt returned to cold salt tank. Measure the temperature drop across the east and west string of panels. Receiver loop heat tracing is turned off.
2. **Testing at 700 °F** – By controlling the receiver outlet temperature and mixing with the cold salt tank, or by mixing hot salt with cold salt via an inter-tank transfer of salt, raise the cold salt tank temperature to 700 °F. Receiver loop heat tracing is turned off.

Flow cold salt at 700 °F ±20 °F through the receiver with no heliostats tracking the receiver. Measure the temperature drop across the east and west string of panels. Note: Only testing at 550 °F conducted during power production phase.

Power On Testing

1. Place receiver in steady-state operation with full field (sets 1 and 2) with a receiver outlet temperature of 1,050 °F ±25 °F.
2. At 1/2 hour before solar noon, command set 2 of heliostats to standby.
3. At solar noon, command set 2 of heliostats back on track.
4. At 1/2 hour after solar noon, command set 1 of heliostats to standby.
5. At 1 hour after solar noon, command set 2 of heliostats to track. Test is complete. Normal operations may resume.
6. Repeat test sequence on subsequent days with a receiver outlet temperature set point of 850 °F ±25 °F and 700 °F ±25 °F.
7. Repeat test at 1,050 °F ±25 °F setpoint using a 25 percent and 50 percent field combination instead of the 100 percent and 50 percent combination.



Tracking Sequence of Complementary Groups of Heliostats

Note: Some of the Power On and Power Off tests will need to be interspersed with other tests in order to obtain the desired wind conditions.

Note: During power production, only tests using steps 1 through 5 will be performed. This reduces the extent of testing.

Data Requirements:

Key Instruments – IR Telescope required to measure front tube temperatures. Record equipment or receiver coating changes which have occurred since the last efficiency test which may impact this test.

Duration – Ten test days plus five tests for 2 hours surrounding solar noon conducted on the same days as Test 5. This should provide 15 Power On tests and at least 6 Power Off tests. Some of these tests should be interspersed with later tests to obtain desired wind conditions.

Frequency – Not applicable

Data Reduction:

Power Off Testing

1. Compute the thermal loss due to radiation, convection, and conduction from the mass flow rate and temperature drop as follows:

$$L_{rec_n} = FI5102_n * \left[cp(TI5366A_n) * TI5366A_n - cp(TI5104_n) * TI5104_n\right] + FI5302_n * \left[cp(TI5166A_n) * TI5166A_n - cp(TI5304_n) * TI5304_n\right]$$

where:

FI = mass flowrate, lbm/sec. Flowmeter data, delta pressure data, and receiver pump speed data will be compared to assure the best estimate of this flowrate.

cp = specific heat, Btu/lbm-°F. The specific heat of the salt will be computed by a subroutine using temperature curve fits.

TI = temperature, °F.

n = counter for delineating one data sample from another.

2. Compute the average thermal loss as follows:

$$L_{avg} = \frac{\sum_{n=1}^{N} L_{rec_n}}{N}$$

where N is the total number of samples.

3. The receiver efficiency is not directly calculated in this method of testing. To compute receiver efficiency, the receiver losses, L, must be computed for the operating temperature based on extrapolation from L_{avg}. The efficiency is then calculated as:

$$\eta_{rec} = \frac{\alpha}{1 + \frac{L_{avg}}{P_{abs}}}$$

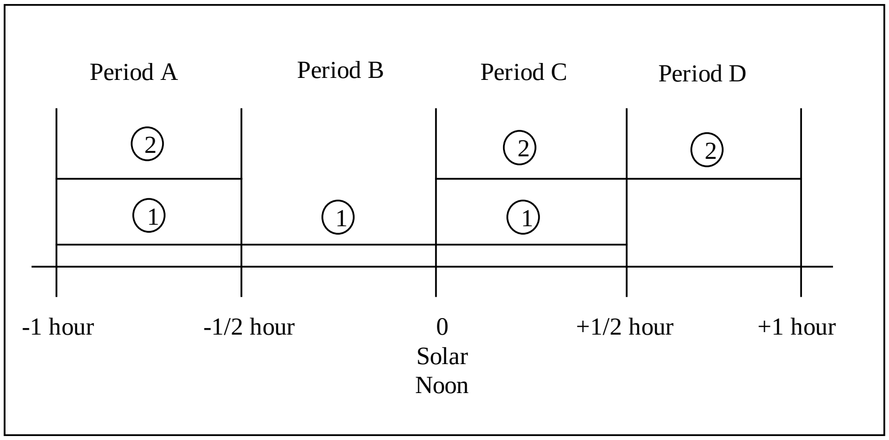
where α is the receiver absorptivity, and P_{abs} is the power absorbed by the receiver.

Power On Testing

Theory

The basics of the power on receiver efficiency test are to:

1. Split the heliostat field into two complementary groups, groups 1 and 2, symmetrically dispersed about the receiver, operate the receiver at part load with one group just prior to solar noon.
2. Operate sequentially at full power (both groups), then group 1, then full power, and lastly group 2. The operation is timed to occur symmetrically about solar noon as shown in the figure below.



Tracking Sequence of Complementary Groups of Heliostats

The rationale for this sequence of operational states is as follows. Defining the average power incident on the receiver, $\overline{P}_{inc}$, as:

$$\overline{P}_{inc} = \frac{1}{N}\sum_{n=1}^{N} P_{inc_n}$$

where:

P_{inc} = power incident on the receiver, MWt.

n = index identifying one data measurement from another. Data is taken at regular intervals.

N = total number of data measurements.

Because of the symmetry of the solar radiation about solar noon, by inspection we can write:

$$\overline{P}_{inc_A} = 2\overline{P}_{inc_D} \qquad \text{[Equation 6.1]}$$

$$\overline{P}_{inc_C} = 2\overline{P}_{inc_B} \qquad \text{[Equation 6.2]}$$

where the letters A through D indicate the time period over which the incident power was averaged. We can multiply each side of the above equations by the absorptivity, α, and note that the following is true:

$$\alpha\overline{P}_{inc} = \overline{P}_{abs} + L \qquad \text{[Equation 6.3]}$$

where:

$\overline{P}_{abs}$ = average power absorbed by the receiver, MWt.

L = combined receiver conductive, convective, and radiative losses, MWt.

The important assumption to be made here is:

> **When operating under flux from the heliostat field and delivering rated temperature (1,050 °F) salt, the temperature distributions on the surface and throughout the receiver are identical. Therefore, the thermal losses, L, are constant independent of the incident power.**

Though this is not entirely true, it is close enough to true given the uncertainty in the measurements that the losses, L, can be considered constant.

Using the assumption of constant losses, we can rewrite Equations 6.1 and 6.2 using Equation 6.3 as:

$$\overline{P}_{abs_A} + L = 2\overline{P}_{abs_D} + 2L \qquad \text{[Equation 6.4]}$$

$$\overline{P}_{abs_C} = 2\overline{P}_{abs_B} + 2L \qquad \text{[Equation 6.5]}$$

Adding Equations 6.4 and 6.5 together and solving for L:

$$L = \frac{1}{2}\left[\overline{P}_{abs_A} + \overline{P}_{abs_C} - 2\overline{P}_{abs_B} - 2\overline{P}_{abs_D}\right]$$ [Equation 6.6]

Now the receiver losses can be calculated based only on the salt mass flowrate, and the inlet and outlet thermocouple measurements. To compute the receiver efficiency, the receiver absorptivity must be measured and then the following equation used:

$$\eta_{rec} = \frac{\alpha}{1 + \frac{L}{P_{abs}}}$$ [Equation 6.7]

This process allows the calculation of the receiver efficiency subject only to the uncertainties of the flowrate measurement, inlet and outlet temperature measurement, and the receiver absorptivity measurement. The uncertainties in the field performance such as reflectivity, cosine effect, and alignment are avoided.

Implementation

1. Review data for validity and to determine where steady-state conditions were achieved.
2. Compute the receiver absorbed power for each measurement of each period using the equation below:

$$P_{abs_n} = FI5102_n * \left[cp(TI5366A_n) * TI5366A_n - cp(TI5104_n) * TI5104_n\right] + FI5302_n * \left[cp(TI5166A_n) * TI5166A_n - cp(TI5304_n) * TI5304_n\right]$$

where:

FI	=	mass flowrate, lbm/sec. Flowmeter data, delta pressure data, and receiver pump speed data will be compared to assure the best estimate of this flowrate.
cp	=	specific heat, Btu/lbm-°F. The specific heat of the salt will be computed by a subroutine using temperature curve fits.
TI	=	temperature, °F.
N	=	counter for delineating one data sample from another.

3. Compute the average power absorbed by the receiver during each period, A through D, as shown below:

$$\overline{P}_{abs} = \frac{1}{N}\sum_{n=1}^{N} P_{abs_n}$$

4. Use Equations 6.6 and 6.7 to compute the receiver efficiency.

Deliverables:

1. Receiver efficiency as a function of temperature level and wind conditions.
2. Receiver tube stress estimates from IR camera and thermocouple data.
3. Comparison to prediction of temperature distribution and efficiency.

Acceptance Criteria:

Phase II – 15 Power On and 6 Power Off tests at conditions as specified.

Phase IV – 1 Power On and 1 Power Off test each year.

Resources Required:

Pre-Test – One test engineer to review Power Off testing to determine if a wind and ambient temperature condition exists where salt may be frozen in the receiver tubing.

One test engineer and one operator. Tasks are:

a. Prepare heliostat control file for automated sequencing of heliostat commands in order to perform tests.
b. Review any test specific operating procedures.

Test – Test engineer and regular operations staff.

Post-Test – One test engineer perform data reduction as called out above.

1.7 Receiver Steady-State Performance

Test No.: 7 **Receiver Steady-State Performance**

Description: This series of tests will examine the response of the two receiver loops to variations in the power level, time of day, wind speed, and receiver outlet temperature. The adequacy of a single salt crossover will be assessed.

Objectives:

1. Produce a performance map indicating when the receiver cannot provided rated outlet salt temperature, or cannot accept full incident flux, and to what extent the outlet temperature is degraded.
2. Compute the receiver losses as a function of wind speed.
3. Assess adequacy of a single salt crossover.

Prerequisites:

Preanalysis	–	Predicted flux distributions for 64 points during the year from the University of Houston. Calculated receiver panel flux limitations as a function of temperature and mass flow rate from inlet to outlet provided by receiver supplier.
Calibration	–	None
Plant Operating Status	–	Plant start-up complete
Weather	–	Clear sky conditions during data collection
Other	–	None

Precautions:

None

Test Sequence:

Operate the plant normally. Bias data taking to early morning and late afternoon.Some tests should be on and near the summer solstice. Fill in Table 2-1 below.

Note: Some of these tests will need to be interspersed with other tests in order to obtain the desired wind conditions.

Note: Some of these test days should be dispersed throughout the year in order to cover the seasonal effects (runs near summer solstice are most important).

Table 2-1. Outlet Temperature and Wind Test Matrix

Time of Day	Day of Year	TI5166A	TI5366A	TI5024	Wind Speed
					0 – 5 mph
					5 – 15 mph
					15 – 25 mph
					25 – 40 mph
					0 – 5 mph
					5 – 15 mph
					15 – 25 mph
					25 – 40 mph
					0 – 5 mph
					5 – 15 mph
					15 – 25 mph
					25 – 40 mph
					0 – 5 mph
					5 – 15 mph
					15 – 25 mph
					25 – 40 mph

Data Requirements:

Key Instruments – Plant instrumentation will used and recorded as normal by the Data Acquisition System.

Duration – Twenty test days. Emphasis will be given to early morning and late-afternoon data collection.

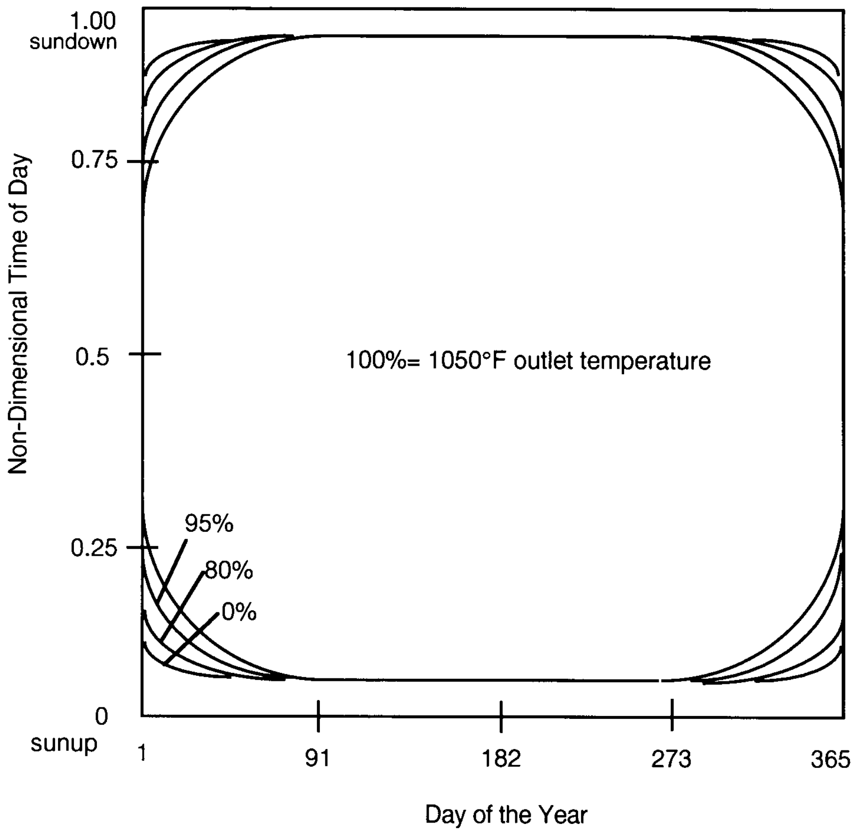
Frequency – Not applicable

Data Reduction:

1. Plot the temperature versus flow path distance for the east and west receiver loops.
2. Compute the absorbed power for each panel.
3. Cross plot power versus temperature.
4. Compare with design curves.
5. Assess.

Performance Chart

Performance in the sense of this chart, is the ability of the receiver to produce hot salt at the rated outlet temperature of 1,050 °F. A proposed mapping of the data is shown in the figure below.



Deliverables:

1. Receiver loop performance as a function of variables listed.
2. A map of operating conditions that could overstrain the receiver tubes in some panels together with the magnitudes and durations of these conditions.
3. Allowable receiver turndown ratios in both flow loops as a function of the listed parameters.

4 The reduction required, if any, in the outlet salt temperature set point, or incident flux, in either flow loop as a function of the parameters listed.

4. Lessons learned which can help to optimize the heliostat field layout with the receiver flow paths and crossovers.
5. Receiver losses as a function of wind speed.

Acceptance Criteria:

Complete the test matrix.

Resources Required:

Pre-Test	–	One test engineer to evaluate if any of the test conditions may result in salt freezing in the receiver
Test	–	Test engineer and regular operations staff

Post-Test – One test engineer to perform data reduction

1.8 Thermal Losses Throughout the Plant

Test No.: 8 **Thermal Losses Throughout the Plant**

Description: Measure the 24 hour thermal losses due to convection, conduction and radiation from the plant equipment and piping.

Objectives:

1. Acquire data for a detailed heat balance for the plant.
2. Measure the sources of heat loss in the plant.
3. Acquire data to design the heat losses for the commercial plant.

Prerequisites:

Preanalysis	–	Heat trace vendor calculations. Calculation of insulation effectiveness on riser, downcomer, hot tank, and cold tank.
Calibration	–	None
Plant Operating Status	–	All systems functional under automatic control
Weather	–	Not applicable
Other	–	Insulation dry during data collection to establish a baseline

Precautions:

None

Test Sequence:

Note: Thermal losses from the receiver while drained are covered under Test 9, Parasitic Power Consumption Tests

Hot Tank, Cold Tank, Hot Sump, Cold Sump and High Pressure Air Receiver, and Steam Generator Thermal Losses:

Isothermal Test (All Vessels)

1. During a planned plant shutdown or long term hold with the hot or cold tank near or at its minimum level, monitor the heat tracing and immersion heater power consumption as they maintain the tanks at temperature. A minimum 1-week hold period is desired. Opportunities to take and review data at other combinations of fill should be pursued as budget and time permit.
2. During a planned plant shutdown or long-term hold, monitor the heat tracing and immersion heater power consumption as they maintain the temperature of the hot sump, cold sump, high pressure air receiver, and steam generator. A minimum 3-day hold period is desired.

Cooldown Test (Storage Tanks and Sumps Only)

1. During a planned plant shutdown or long-term hold with, shut off all heat tracing and immersion heaters to the hot tank and cold tank. Monitor the tank thermocouples to determine the mean tank temperature. A minimum 1-week hold period is desired. It is expected that the hot tank will be at its minimum level and the cold tank at its maximum level for this test. Opportunities to take and review data at other combinations of fill should be pursued as budget and time permit.
2. During a planned plant shutdown or long-term hold, shut off all heat tracing and immersion heaters to the hot sump and cold sump. Monitor their temperatures to determine mean temperature. A minimum 3-day hold period is desired.

Salt Loop Thermal Losses:

1. **Receiver Loop Stagnant Flow** – Halt flow in the riser and downcomer. Monitor the heat tracing to determine the heat losses. Perform at 550 °F ±20 °F and 700 °F ±20 °F initial temperature and heat tracing set point.
2. **Receiver Loop Empty** – Drain the riser and downcomer. Monitor the heat tracing to determine the heat losses. Perform at 550 °F ±20 °F and 700 °F ±20 °F initial temperature and heat tracing set point.
3. **IR Survey** – Use IR cameras to locate heat shorts through the insulation, pipe hangers, etc. Estimate the heat loss rate. Surveys are to be conducted at night or in the early morning.
4. **Miscellaneous** – Use heat tracing data to compute piping and valve thermal losses.

Note: The thermal losses of the steam generator will be determined as part of test 3.

Data Requirements:

Key Instruments	–	IR camera and image processing system to generate false color video for temperatures between 30 °F and 400 °F and video recorder for the IR survey.
Duration	–	As required for IR survey. Repeat whole test in conjunction with test 17.
Frequency	–	Perform IR survey every 6 months

Data Reduction:

Hot Tank, Cold Tank, Hot Sump, Cold Sump and High Pressure Air Receiver, and Steam Generator Thermal Losses:

Cooldown Tests

1. For each set of temperature datapoints, compute the energy in the tank, sump, or air receiver as follows:

$$E_{\tan k_i} = \sum_{n=1}^{N} \rho_n c_{p_n} V_n T_n$$

where:

E_{tank_i} = energy in the tank at time i.

ρ_n = effective density of tank contents, tank wall, and insulation associated with temperature T_n.

cp_n = effective specific heat of tank contents, tank wall, and insulation associated with temperature Tn.

V_n = volume of tank associated with temperature T_n.

n = index for temperature measurement.

N = number of measured tank temperatures at time i.

The vessel must be split into volumes associated with each thermocouple. Since the volume may have all salt, all air, or part salt/part air, plus the metal and insulation, the energy in the volume must be determined by the evaluator based on the state of the vessel at the beginning of the cooldown test.

2. Compute the energy weighted internal temperature of the vessel, T_{int_i}, as follows:

$$T_{int_i} = \frac{\sum_{n=1}^{N} \rho_n c_{p_n} V_n T_n}{\sum_{n=1}^{N} \rho_n c_{p_n} V_n}$$

3. The energy weighted internal temperature data is fitted to a function of the form:

$$T_{int_i} = (T_{int_0} - T_\infty) e^{-\frac{1}{KR}(t_i - t_0)}$$

where:

T_{int_0} = internal tank temperature at time = t0.

T_∞ = average ambient temperature = $\dfrac{\sum_{t=t_0}^{t=t_i} T_{\infty_i}}{I}$ where I is the total number of time samples. This assumes fixed time intervals between measurements.

K = $\sum_{n=1}^{N} \rho_n cp_n V_n$, taken to be a constant over time.

R = thermal resistance of tank insulation.

ti = time i.

The method is to vary R until the best fit with the experimental data is achieved. This the effective thermal resistance of the vessel insulation. The thermal loss for any internal temperature and ambient temperature can be computed as:

$$P_{loss} = \frac{T_{int} - T_{amb}}{R}$$

Isothermal Tests

1. Monitor the power consumption of the heat tracing and immersion heaters associated with the vessel for a minimum of three temperature cycles. Integrate the electric power consumption:

$$E_{electric} = \sum_{i,j} \left(\frac{P_{i+1,j} + P_{i,j}}{2} \right) (t_{i+1} - t_i)$$

where:

P_{ij}	=	ith measurement of the electric power consumed by the jth heat tracing or heater.
t_i	=	time of the ith measurement.

2. Compute the volume weighted internal temperature of the vessel, T_{int_i}, for the ith measurement as follows:

$$T_{int_i} = \frac{\sum_{n=1}^{N} V_n T_n}{\sum_{n=1}^{N} V_n}$$

where:

V_n	=	volume of tank associated with temperature T_n.
n	=	index for temperature measurement.
N	=	number of measured tank temperatures at time i.

3. Compute the effective thermal resistance of the vessel insulation:

$$R = \frac{1}{E_{electric}} \sum_{i} \frac{(T_{int} - T_{amb})_{i+1} + (T_{int} - T_{amb})_i}{2} (t_{i+1} - t_i)$$

where I is the total number of measurements. The thermal loss for any internal temperature and ambient temperature can be computed as:

$$P_{loss} = \frac{T_{int} - T_{amb}}{R}$$

Salt Loop Thermal Losses:

Receiver Loop Stagnant Flow and Empty Losses

1. Monitor the power consumption of the heat tracing associated with the piping for a minimum of three temperature cycles. Integrate the electric power consumption:

$$E_{electric} = \sum_{i,j} \left(\frac{P_{i+1,j} + P_{i,j}}{2} \right) (t_{i+1} - t_i)$$

where:

P_{ij} = ith measurement of the electric power consumed by the jth heat tracing.

t_i = time of the ith measurement.

2. Compute the volume weighted internal temperature of the piping, T_{int_i}, for the ith measurement as follows:

$$T_{int_i} = \frac{\sum_{n=1}^{N} V_n T_n}{\sum_{n=1}^{N} V_n}$$

where:

V_n = volume of pipe, salt, and insulation associated with temperature T_n.

n = index for temperature measurement.

N = number of measured tank temperatures at time i.

3. Compute the effective thermal resistance of the pipe insulation:

$$R = \frac{1}{E_{electric}} \sum_{i} \frac{(T_{int} - T_{amb})_{i+1} + (T_{int} - T_{amb})_i}{2} (t_{i+1} - t_i)$$

where I is the total number of measurements. The thermal loss for any internal temperature and ambient temperature can be computed as:

$$P_{loss} = \frac{T_{int} - T_{amb}}{R}$$

IR Survey

Video will be reviewed and P&ID marked up to indicate temperature distribution.

Miscellaneous Losses

Follow the method developed for the Receiver Loop Stagnant Flow and Empty losses.

Deliverables:

1. Thermal performance of thermal storage tank, sumps, high pressure air receiver, and steam generator insulation.
2. Effective thermal resistance and heat losses of the riser and downcomer insulation

3. Tabulation of heat losses in the tanks, sumps, piping, heat exchangers, and major equipment. Regions showing excessive heat loss will be noted for plant maintenance.
4. Lessons learned regarding prediction of thermal losses. Recommendations for future designs.

Acceptance Criteria:

Measurements and assessment complete. All major system have thermal losses characterized. Recommendations for improvement of Solar Two submitted to owner.

Resources Required:

Pre-Test	–	Hot and Cold Tank Thermal Losses: Test engineer to determine whether heel is sufficient for isothermal conditions on the interior of tank.
IR Survey	–	Test engineer and instrument technician for instrument calibration, IR camera
Test	–	Test engineer and regular operations staff
Post-Test	–	Test engineer, data processing equipment per Test and Evaluation Plan, video recorder

1.9 Parasitic Power Consumption Tests

Test No.: 9 **Parasitic Power Consumption Tests**

Description: Measure the electricity consumption throughout the plant as a function of the plant's operating state, output, and overnight hold.

Objectives:

1. Parasitic electricity consumption magnitude and source for different operating and shutdown conditions.
2. Data to be used to optimize plant operations in Tests 14, 15 and 16.

Prerequisites:

Preanalysis	–	Power rating of major plant components from manufacturer's data
Calibration	–	None
Plant Operating Status	–	Normal operation
Weather	–	Not applicable
Other	–	Thermal insulation dry during data collection to establish baseline

Precautions:

None

Test Sequence:

1. Monitor power consumption per Table 9-1. Monitor high priority items first and then continue to lower priority items as budget and time allow. Separate the power consumed based on the plant state or transition. If the power for a piece of equipment cannot be measured or determined through the DAS instrumentation, then a portable wattmeter may be attached to obtain the data. The testing here takes place in conjunction with Test 12.

Table 9-1. Equipment to Monitor for Power Consumption

Equipment	Load Center	Priority	Dedicated Wattmeter Exist Yes/No
Cold Salt Pump M-250A		High	N
Cold Salt Pump M-250B		High	N
Attemperation Pump P-852		High	N
Hot Salt Pump M-850A		High	N
Hot Salt Pump M-850B		High	N
Recirculation Pump P-853		High	N
Recirculation Heater H-851		High	N

Table 9-1. Equipment to Monitor for Power Consumption (continued)

Equipment	Load Center	Priority	Dedicated Wattmeter Exist Yes/No
Feedwater Pump		High	
Heliostat Field		High	Y
Plant Lighting and Air Conditioning		High	N
Administration Building Power		High	Y
Cooling Tower		High	Y
Receiver Lower Header Heat Tracing		High	N
Receiver Upper Header Heat Tracing		High	N
Receiver Inlet Tank Heat Tracing		High	N
Receiver High Pressure Air Receiver HT		High	N
Receiver Outlet Tank Heat Tracing		High	N
Receiver Piping Heat Tracing		High	N
Riser Heat Tracing		High	N
Downcomer Heat Tracing		High	N
Cold Sump Heat Tracing		High	N
Cold Sump Immersion Heaters		High	N
Hot Sump Heat Tracing		High	N
Hot Sump Immersion Heaters		High	N
Cold Tank Heat Tracing		High	N
Cold Tank Immersion Heaters		High	N
Hot Tank Heat Tracing		High	N
Hot Tank Immersion Heaters		High	N
Preheater E-852 Heat Tracing		High	N
Boiler E-851 Heat Tracing		High	N
Superheater E-850 Heat Tracing		High	N
Steam Generator Salt Piping Heat Tracing		High	N
Condensate Pump		Low	N
Air Compressor CP-951A		Low	N
Air Compressor CP-951B		Low	N
Condenser Vacuum Pump P-941		Low	N
Cooling Water Pump P-901		Low	N
Raw/Service Water Pump P-703		Low	N
Raw/Service Water Pump P-704		Low	N

Data Requirements:

Key Instruments – Watt meter(s)

Duration – As staffing is available over latter 6 months of Test and Evaluation Phase

Frequency – One sample per minute

Other – Note weather conditions during measurement

Data Reduction:

1. Catalog parasitic power data according to plant state as shown in Table 9-2 and for plant transitions as shown in Table 9-3.

Table 9-2. Parasitic Power Loads for Plant States (Watts)

Load	Long-Term Hold	Short-Term Hold	Standby	Ready	Operation	Aux. Steam	Cloud Standby
Load Center A – Total							
Receiver Lower Header Heat Tracing							
Receiver Upper Header Heat Tracing							
Receiver Inlet Tank Heat Tracing							
Receiver High Press. Air Receiver HT							
Receiver Outlet Tank Heat Tracing							
Receiver Piping Heat Tracing							
Riser Heat Tracing							
Downcomer Heat Tracing							
Cold Sump Heat Tracing							
Cold Sump Immersion Heaters							
Hot Sump Heat Tracing							
Hot Sump Immersion Heaters							
Cold Tank Heat Tracing							
Cold Tank Immersion Heaters							
Hot Tank Heat Tracing							
Hot Tank Immersion Heaters							
Preheater E-852 Heat Tracing							
Boiler E-851 Heat Tracing							
Superheater E-850 Heat Tracing							
Load Center B – Total							
Cold Salt Pump M-250A							
Cold Salt Pump M-250B							
Attemperation Pump P-852							
Hot Salt Pump M-850A							
Hot Salt Pump M-850B							

Table 9-2. Parasitic Power Loads for Plant States (Watts) (continued)

Load	Long-Term Hold	Short-Term Hold	Standby	Ready	Operation	Aux. Steam	Cloud Standby
Recirculation Pump P-853							
Recirculation Heater H-851							
Feedwater Pump							
Condensate Pump							
Air Compressor CP-951A							
Air Compressor CP-951B							
Condenser Vacuum Pump P-941							
Cooling Water Pump P-901							
Raw/Service Water Pump P-703							
Raw/Service Water Pump P-704							
Heliostat Field							
Plant Lighting and Air Conditioning							
Administration Building Power							
Cooling Tower							
Total Parasitic Power							

Table 9-3. Parasitic Power Loads for Plant Transitions

Load	LT Hold to ST Hold	ST Hold to Standby or Aux. Stm	Standby to Ready	Ready to Operation	Aux. Stm to Ready
Load Center A – Total					
Receiver Lower Header Heat Tracing					
Receiver Upper Header Heat Tracing					
Receiver Inlet Tank Heat Tracing					
Receiver High Press. Air Receiver HT					
Receiver Outlet Tank Heat Tracing					
Receiver Piping Heat Tracing					
Riser Heat Tracing					
Downcomer Heat Tracing					
Cold Sump Heat Tracing					
Cold Sump Immersion Heaters					
Hot Sump Heat Tracing					
Hot Sump Immersion Heaters					
Cold Tank Heat Tracing					
Cold Tank Immersion Heaters					
Hot Tank Heat Tracing					
Hot Tank Immersion Heaters					

Table 9-3. Parasitic Power Loads for Plant Transitions (continued)

Load	LT Hold to ST Hold	ST Hold to Standby or Aux. Stm	Standby to Ready	Ready to Operation	Aux. Stm to Ready
Preheater E-852 Heat Tracing					
Boiler E-851 Heat Tracing					
Superheater E-850 Heat Tracing					
Load Center B – Total					
Cold Salt Pump M-250A					
Cold Salt Pump M-250B					
Attemperation Pump P-852					
Hot Salt Pump M-850A					
Hot Salt Pump M-850B					
Recirculation Pump P-853					
Recirculation Heater H-851					
Feedwater Pump					
Condensate Pump					
Air Compressor CP-951A					
Air Compressor CP-951B					
Condenser Vacuum Pump P-941					
Cooling Water Pump P-901					
Raw/Service Water Pump P-703					
Raw/Service Water Pump P-704					
Heliostat Field					
Plant Lighting and Air Conditioning					
Administration Building Power					
Cooling Tower					
Total Parasitic Power					

2. Characterize the receiver variable-speed cold salt pumps for optimization studies. Variables to be correlated are:

   Mass flow rate and electric power consumption

Deliverables:

1. Tables of parasitic power load for load centers, major equipment, and heat tracing groups as a function of operating state and transition.
2. Comparison of recorded values with prediction.
3. Suggestions for reducing the parasitic power load.
4. Lessons learned for future plants.

Acceptance Criteria:

Breakdown sum is 95 percent or greater of the measured plant load (JIX5001).

Resources Required:

Pre-Test	–	Test engineer and instrument technician for wattmeter calibration and installation on selected equipment as required. Wattmeter.
Test	–	Test engineer and operations staff.
Post-Test	–	Test engineer, data processing equipment per Test and Evaluation Plan.

1.10 Receiver Start-up Following a Heavy Rain

Test No.: 10 Receiver Start-up Following a Heavy Rain

Description: Determine the effect on receiver start-up due to intrusion of rain water into receiver insulation.

Objectives:

1. Confirm start-up readiness of the receiver following a heavy rain.
2. Determine any constraints on start-up following rain.
3. Establish procedure for future start-ups after rain.

Prerequisites:

Preanalysis	–	Establish ‘dry’ start-up baseline in Test 7
Calibration	–	None
Plant Operating Status	–	Normal operation
Weather	–	Heavy rain prior to start-up
Other	–	None

Precautions:

None

Test Sequence:

1. During and immediately following a heavy rain, carefully monitor all thermocouples used to confirm that the receiver loop is warm enough to start. Note any time delays before the receiver can be started.
2. Conduct a normal receiver warm-up and start as soon after the rain as the loop is ready for start-up.
3. Note any deviations in the time required for start-up or in the temperature distributions for this case compared with other operations. Note any increased usage of heat tracing.

Data Requirements:

Key Instruments	–	None
Duration	–	As required
Frequency	–	When weather conditions occur during the Test and Evaluation year and when possible thereafter

Data Reduction:

1. Establish baseline start-up parameters of time to start, header temperatures, and header heat trace power.
2. Breakout comparative data from the post-rain receiver start data.

3. Determine the differences and similarities.
4. Compute the energy penalty, if any, associated with a post-rain receiver start. Determine if a post-rain start presents a thermal stress risk to receiver.
5. Suggest means of mitigating energy loss or receiver damage.

Deliverables:

1. Difference in start-up time, if any, due to intrusion of rain water into receiver insulation.
2. Heat tracing requirements for receiver start-up after a heavy rain.
3. Record total precipitation and average rate of rainfall.
4. Revised hardware or operating procedures.
5. Lessons learned.

Acceptance Criteria:

Record and evaluate one or more receiver start-ups after a heavy rain.

Resources Required:

Pre-Test	–	Test engineer to prepare baseline data
Test	–	Test engineer and operations staff
Post-Test	–	Test engineer, data processing equipment per Test and Evaluation Plan

1.11 Receiver Drain During High Wind Conditions

Test No.: 11 Receiver Drain During High Wind Conditions

Description: Obtain temperature data of the receiver while draining under high wind (>30 mph) conditions for comparison to similar operations at low wind (<10 mph) conditions.

Objectives:

1. Confirm ability to drain the receiver safely in all wind conditions.
2. Determine any constraints on draining the receiver in high winds.
3. Provide data for use in designing the commercial receiver to allow safe draining under all wind conditions.

Prerequisites:

Preanalysis	–	Prediction of drain transient from receiver manufacturer. Establish low wind drain baseline in Test 7. Verify that high wind drain is safe during the Start-up and Acceptance testing.
Calibration	–	None
Plant Operating Status	–	Receiver shown to be safely drainable in all wind conditions
Weather	–	Specified wind conditions
Other	–	None

Precautions:

Monitor receiver to prevent or detect freezing.

Test Sequence:

1. During normal receiver draining operations under stagnant and low-wind conditions, record all receiver back tube temperatures, salt temperatures and the drain times.
2. Repeat these measurements for cases with higher wind speeds. Note any reduction in temperatures or increases in drain times.
3. Use the infrared camera to measure selected front tube temperatures during these tests and to verify that the receiver is drained.

Data Requirements:

Key Instruments	–	IR camera
Duration	–	As required
Frequency	–	When weather conditions permit. Hopefully high winds will occur during Test 7.

Data Reduction:

1. Compute the drain time of each panel.
2. Compare drain time and temperatures with low wind baseline.
3. Compute the design margin.

Deliverables:

1. Confirmation that the receiver can be drained in all wind conditions.
2. Increase in salt drain time as a function of wind speed and direction on a per panel basis.
3. Decrease in receiver temperature during draining as a function of wind speed.
4. Comparison to design predictions.
5. Lessons learned.

Acceptance Criteria:

Record and evaluate 1 or more drains during high wind conditions

Resources Required:

Pre-Test	–	Test engineer to prepare or acquire baseline data
Test	–	Test engineer and operations staff
Post-Test	–	Test engineer, data processing equipment per Test and Evaluation Plan

1.12 Optimization of Receiver Loop Operations

Test No.: 12 Optimization of Receiver Loop Operations

Description: Determine how to maximize receiver loop output.

Objectives:

1. Determine the operating procedures that will yield the maximum collected energy.
2. Develop data to allow the commercial receiver loop to be designed for maximum operational availability.

Prerequisites:

Preanalysis	–	Daytime portion of Test 13 complete before this test. Tests 1 through 11, and 13 and their data reduction complete before optimization process begins.
Calibration	–	TBD
Plant Operating Status	–	Normal operation
Weather	–	Not applicable
Other	–	Tests 12 and 13 must be complete 60 days or more before the end of the Test and Evaluation year. This is to provide the operations staff time to update the plant operating procedures as required by their contract.

Precautions:

Normal operating precautions. Changes to procedures must be assessed for potential negative impacts on plant equipment warranty, risk of damage, and safety.

Test Sequence:

1. Operate the receiver loop and heliostat field in combination per the operations manual.
2. Review data from tests 1 through 11, and test 13, and develop and test new procedures and software that could reduce the time spent in start-up and other state transitions where benefit is indicated.
3. Develop optimum strategy for operating through periods with intermittent clouds.
4. Develop and test procedures that would simulate operation of a commercial plant more closely.
5. Continue this process iteratively until benefit of any change to plant production is minimal.

Data Requirements:

Key Instruments	–	None
Duration	–	0 to 3 months depending on success and information gained in preceding tests

Frequency – Not applicable

Data Reduction:

The nature of the optimization process depends on the results of the preceding tests. Therefore, specific data reduction methods cannot be written at this time.

Deliverables:

1. Recommend revisions to the receiver loop operating procedures for all operating states to be used in the balance of the test program to maximize energy collection.
2. Start-up times broken down according to steps in the procedure.
3. Recommended optimum strategy for operating through periods of intermittent cloudiness including the hold condition and duration as a function of the weather prediction and potential integrated insolation.
4. Lessons learned which can be used to increase the energy collected in the commercial plant.
5. Identify plant modifications to improve plant availability.

Acceptance Criteria:

Optimization continues until all major improvements tested and evaluated experimentally. Recommendations delivered to owner.

Resources Required:

Pre-Test	–	None (preparation for this test performed as part of data reduction and evaluation on previous tests)
Test	–	Three to five test engineers and operations staff
Post-Test	–	One to two test engineers, data processing equipment per Test and Evaluation Plan

1.13 Overnight Thermal Conditioning

Test No: 13 Overnight Thermal Conditioning

Description: Investigate three alternative methods for thermally conditioning the receiver loop for start-up.

Objectives:

1. Select the preferred method of thermal conditioning the plant for start-up and the preferred conditions during overnight and daytime hold periods.
2. Develop data to allow the commercial receiver loop to be designed with the optimum thermal conditioning capability for its size.

Prerequisites:

Preanalysis	–	Predict the advantages/disadvantages of each method. Characterize baseline conditioning method (method C) during test 7. Do stress analysis for rapid heatup with heat tracing.
Calibration	–	None
Plant Operating Status	–	Overnight shut-down state (short-term hold). Insure that the heat tracing is completely functional in the receiver loop.
Weather	–	All tests should occur in the same season and general weather patterns
Other	–	None

Precautions:

Review test for overstress (thermal) and potential for salt freezing.

Test Sequence:

It is assumed that intermittent salt recirculation (method C) has been the method used for overnight thermal conditioning up to this point. It is anticipated that this may not be particularly efficient because the system design was not optimized for this method. This test will attempt to improve the efficiency of this baseline method and compare it to the other two alternatives listed.

Testing will be conducted first during the day, simulating an overnight hold. This permits the operations and engineering staff to conduct a concentrated effort without working through a graveyard shift.

Once the overnight conditioning methods have been well characterized and their procedures developed during daytime testing, each method will be implemented for actual overnight short-term holds.

The following tests should be conducted prior to test 12. Overnight conditioning results for Solar Two will have limited direct applicability to commercial plants.

1. Test the following three alternative methods for thermally conditioning the receiver loop for start-up for a minimum of 2 weeks each:
   A. Maintain the loop warm overnight with the electric trace heaters.
   B. Empty the pipes and allow the loop to cooldown to a setpoint temperature (may be ambient) following operation, then simulate a rapid warm-up to start-up temperatures using the heat tracing.
   C. Recirculate "cold" salt through the receiver bypass line by bumping the receiver pump in order to maintain part of the loop warm and ready for start-up overnight and through daytime shutdown periods.
2. An 8 hour test day can be used initially to simulate an overnight hold condition. All tests should be conducted for the same hold time (except test 1B as described below).
3. All electrical and thermal parasitic losses should be measured with maximum accuracy for these tests.
4. Test 1B will require a longer test duration to simulate losses during a 6-hour hold time and a 2-hour warm-up time. The actual warm-up time will approximate 8 hours.
5. Additional tests will be conducted with method 1C to collect data which will allow a more accurate evaluation of this method for the commercial plant.
6. The readiness of the system to start-up and any differences in start-up times will be noted for these alternatives.

Data Requirements:

Key Instruments	–	None
Duration	–	Approximately 6 weeks should be allocated to these tests in addition to the data collected on mode A during Test 12
Frequency	–	Not applicable

Data Reduction:

For All Methods – Total electricity usage for overnight trace heating, duty cycle and rating for each circuit, selected salt temperatures throughout the receiver loop, ambient temperature and wind conditions periodically during the test, test duration and readiness for morning start-up. Assess in conjunction with Test 8 to determine if insulation is adequate or flawed.

For Method C – Add the electricity usage of the salt recirculation pump and the flowrate and temperatures (inlet and outlet) of the salt supplied for thermal conditioning.

Deliverables:

1. Electrical and thermal energy required for overnight thermal conditioning with each of the candidate modes.
2. Identification of other issues, such as operating complexity, or system readiness for start-up, that could influence selection of the preferred mode.
3. Design modifications for Solar Two which would reduce energy usage for overnight thermal conditioning.

4. Selection of the preferred mode for overnight thermal conditioning of a commercial plant.
5. The receiver loop design and the operations that should be used in the commercial plant to minimize losses due to overnight thermal conditioning.
6. A prediction of the electrical and thermal energy that would be required for this function in the commercial plant.

Acceptance Criteria:

Preferred method selected for Test 12.

Resources Required:

Pre-Test	–	One test engineer to prepare comparison of methods and assemble baseline information on method C
Test	–	One test engineer and operations staff
Post-Test	–	One test engineer, data processing equipment per Test and Evaluation Plan

1.14 Optimum Plant Operation

Test No.: 14 Optimum Plant Operation

Description: Maximize the net power produced. This test will incorporate procedures developed under tests 12 and 13 as its starting basis.

Objectives:

1. Confirm the operating procedures which yield the maximum net power production for the plant.
2. Take and evaluate data to allow the commercial plant to be designed for maximum net power production.

Prerequisites:

Preanalysis	–	Review the test results and O&M documentation for first year of operation
Calibration	–	None
Plant Operating Status	–	All plant modifications performed within budget constraints to bring plant availability to 80 percent or greater complete before start of test
Weather	–	Not applicable
Other	–	None

Precautions:

None

Test Sequence:

1. Operate the full plant to maximize the net power produced.
2. Incorporate procedures developed under Tests 12 and 13.
3. Develop and test new procedures for the steam generator or EPGS operation that would increase net output; e.g., start-up and shutdown, overnight conditioning, and sliding pressure and temperature operation.
4. This should include one test that incorporates the results from Test No. 3 and No. 6 to maximize plant output.

Data Requirements:

Key Instruments	–	None
Duration	–	4 weeks minimum, 6 weeks nominal, 8 weeks maximum
Frequency	–	Not applicable

Data Reduction:

1. Compute the daily input/output for the plant and some intermediate values and tabulate:

   Available Energy

$$E_{field} = \frac{\sum \frac{P_{NIP_{n-1}} + P_{NIP_n}}{2} (t_n - t_{n-1})}{1,000,000} A_{field}$$

where:

E_{field}	=	available energy incident on the heliostat field, MWht.
P_{NIP}	=	insolation based on measurements by the normal incident pyrheliometers, W/m². The readings of the two NIP meters are to be used along with the maintenance records to determine the insolation reading. The process for determining the most accurate reading is described in the Usable Energy section which follows.
A_{field}	=	total reflective area of the heliostat field, m².
t	=	time at which the insolation data is taken, hours.
n	=	counter for delineating one data sample from another.

Usable Energy

Since the Solar Two receiver has a design turndown ratio for the receiver of 20 percent based on an incident solar radiation level of 950 W/m², the usable daily energy is defined as that energy above 190 W/m².

Compute: WHEN $\frac{P_{NIP_{n-1}} + P_{NIP_n}}{2} \geq 190$ THEN

$$E_{usable} = \frac{\sum \left(\frac{P_{NIP_{n-1}} + P_{NIP_n}}{2} \right) (t_n - t_{n-1})}{1,000,000} A_{field}$$

where:

E_{usable}	=	usable energy incident on the heliostat field, MWht.
P_{NIP}	=	insolation based on measurements by the normal incident pyrheliometers, W/m². The readings of the two NIP meters are to be used along with the maintenance records to determine the insolation reading.

The process for determining the insolation reading is:

The average of the two insolation readings unless the two measurements differ by 25 W/m² or more. If the measurements differ by 25 W/m² or more, the reading which is within 25 W/m² of the clear sky insolation as predicted by the clear sky insolation model called out below will be selected, and the other normal incident pyrheliometer will be replaced or recalibrated immediately. If both readings are more than 25 W/m² from the clear sky insolation model prediction, the clear sky insolation model prediction will be used until the normal incident pyrheliometers are repaired or recalibrated.

The insolation readings will be compared against the clear sky insolation model prediction periodically to determine if maintenance procedures are being followed, or to determine if the pyrheliometers and their signal conditioning have suffered a common degradation in performance.

Clear Sky Insolation Model:

There are several models for predicting the clear sky insolation as described in the DELSOL3 Manual by Kistler (SAND86-8018). The Allen model predicts the highest clear sky insolation and is the initial choice. During the Test and Evaluation year, the insolation readings will be compared against the Allen and other models. The model which best predicts the clear sky insolation will be selected for the Power Production Phase.

A_{field}	=	total reflective area of the heliostat field, m².
t	=	time at which the insolation data is taken, hours.
n	=	counter for delineating one data sample from another.

Energy Collected by the Receiver

$$E_{rec} = \sum \left\{ \frac{P_{rec_n} + P_{rec_{n-1}}}{2} \right\} (t_n - t_{n-1})$$

where:

E_{rec}	=	energy collected by the receiver, MWht.
P_{rec_n}	=	power collected by the receiver, MWt.

$$\begin{aligned} P_{rec_n} = {} & FI5102_n * \left[cp(TI5366A_n) * TI5366A_n - cp(TI5104_n) * TI5104_n \right] \\ & + FI5302_n * \left[cp(TI5166A_n) * TI5166A_n - cp(TI5304_n) * TI5304_n \right] \end{aligned}$$

where:

FI	=	mass flowrate, lbm/sec. Flowmeter data, delta pressure data, and receiver pump speed data will be compared to assure the best estimate of this flowrate.
cp	=	specific heat, Btu/lbm-°F. The specific heat of the salt will be computed by a subroutine using temperature curve fits.
TI	=	temperature, °F. The inlet and outlet temperature thermocouples should be calibrated weekly.
t	=	time at which the data is taken, hours.
n	=	counter for delineating one data sample from another.

The summation is to take place over the period of interest when the following conditions are met:

1. One or more receiver pumps have a speed above 0 rpm.
2. The downcomer drag valve, LV5022 or LV5023, is open.
3. The downcomer diversion valves are configured to pass salt to the hot tank as follows: valve TV5027A is open, and valve TV5027B is closed.

Gross Electrical Energy Production

There are two methods to arrive at this number. One is to read the station gross electric watt-hour meter every day at midnight and take the difference between successive readings. The other is to integrate the gross power as follows:

$$E_{gross} = \sum \left\{ \frac{JI5100_n + JI5100_{n-1}}{2} \right\} (t_n - t_{n-1})$$

where:

E_{gross}	=	gross electrical energy generated by the turbine, MWhre.
$JI5100_n$	=	gross electrical power generated by the turbine, MWe.
t	=	time at which the data is taken, hours.
n	=	counter for delineating one data sample from another.

Summations are to be totaled over the period of interest.

Net Electrical Energy Production

There are two methods to arrive at this number. One is to read the station gross electric and parasitic power watt-hour meter every day at midnight and take the difference between successive readings, and then subtract the parasitic energy from the gross energy. For the purposes of determining the plant net electrical power for the contractor performance award, the station watt-hour meter readings taken at midnight will be used.

The other method is to integrate the parasitic power as follows:

$$E_{parasitic} = \sum \left\{ \frac{JIX5001_n + JIX5001_{n-1}}{2} \right\} (t_n - t_{n-1})$$

where:

$E_{parasitic}$	=	parasitic electrical energy, $MWhr_e$.
$JIX5001_n$	=	parasitic electrical power, MW_e.
t	=	time at which the data is taken, hours.
n	=	counter for delineating one data sample from another.

Summations are to be totaled over the period of interest. The net daily electrical energy, E_{net}, is computed as follows:

$$E_{net} = E_{gross} - E_{parasitic}$$

Thermal Energy in Hot and Cold Tanks at Midnight

Since the hot and cold tanks can store energy relative the 'zero' energy temperature of 550 °F, it is necessary to tabulate, at midnight, the energy carried over from 1 day to the next as follows

$$E_{tank_i} = \sum_{n=1}^{N} \rho_n c_{p_n} V_n \left(T_n - 550\right)$$

where:

E_{tank_i}	=	Energy in the tank at time i.
ρ_n	=	effective density of tank contents, tank wall, and insulation associated with temperature T_n.
cp_n	=	effective specific heat of tank contents, tank wall, and insulation associated with temperature T_n.
V_n	=	volume of tank associated with temperature T_n.
n	=	index for temperature measurement.
N	=	number of measured tank temperatures at time i.

This calculation is to be performed for both the hot and cold tank.

The daily operating and maintenance logs such as:

2. Operators log
3. Events log.

Deliverables:

2. System performance data in the form of the plant's daily output, thermal energy collected, gross electric, and net electric output versus the daily integrated insolation.
3. Cumulative plant availability parameters, e.g., Equivalent Forced Outage Rate (EFOR), component Mean Time To Repair (MTTR) and Mean Time Between Failures (MTBF), since start-up testing began.
4. Availability and maintenance data from this specific test, test 14, and revised procedures to maintain a record of such data throughout the balance of the Test and Evaluation tests.
5. The preferred operating states to be used for the balance of the test program.
6. List all predictions used in prior tests.
7. Measured panel deformations and probable cause.
8. Report on receiver absorptive coating performance and maintenance (from Test 6).
8 Report on derated salt outlet temperature operation (from Test 7).

9. Lessons learned in plant design and operation. (What would improve performance, reduce complexity/cost, etc.)

Acceptance Criteria:

Procedures complete.

O&M documentation complete.

Resources Required:

Pre-Test	–	None
Test	–	One test engineer and operations staff
Post-Test	–	One test engineer, data processing equipment per Test and Evaluation Plan

1.15 Power Production

Test No.: 15 Power Production

Description: Operate the plant to achieve maximum electric energy output consistent with insolation levels while performing necessary maintenance and approved testing.

Objectives:

1. Determine plant's annual performance and availability.
2. Document O&M requirements and activities.
3. Improve procedures for plant operation and availability.
4. Identification of potential improvements in O&M procedures.
5. Collect operating data to mitigate risk in estimates of commercial plant design and operating cost.
6. Collect data to extrapolate Solar Two's performance to first commercial plant.
7. Document lessons-learned which could result in design improvements for the commercial plant.
8. Recommend revisions to predictive models, engineering design methods, and management practices for use in a commercial-scale solar central receiver.

Prerequisites:

Preanalysis	–	Predictions of plant performance, especially net annual efficiency
Calibration	–	None
Plant Operating Status	–	Tests 1 through 14 must have been completed and their data evaluated. An equivalent equipment availability of at least 80 percent is a target for this test. If not achieved by the start of Test 14, the necessary refurbishment will be carried out subject to owner approval.
Weather	–	
Other	–	
Precautions	–	None

Test Sequence:

The preferred duration of this test is 24 months, including Test 16. Solar Two will be operated as an on-line, utility generating plant. Every effort will be made to operate the plant at the maximum output achievable with the available insolation. Scheduled maintenance will be performed when such activities will not affect plant production, if feasible. Any other T&E tests will be performed only when approved by the plant manager and scheduled according to plant procedures. Such tests will be held to a minimum. Power dispatching (load shifting) tests and key efficiency tests will be conducted during the power production test. With prior approval from the owner, the O&M staff will be allowed to evaluate different operating and maintenance procedures that have the potential for improving performance and availability.

Data Requirements:

Key Instruments	–	None
Duration	–	24 months
Frequency	–	Not applicable
Other	–	None

Data Reduction:

Data reduction for this test will be continuous over the 2-year power production phase. Energy production and operating and maintenance activities will be monitored. The data will be reviewed with respect to predictions. Computer models for energy production prediction will be updated as necessary. Engineering design recommendations will be revised as operating experience indicates. Operating and maintenance recommended practices will be changed to reflect lessons learned. All improvements will be published.

1. Calculate the energy values below:

Available Energy

$$E_{field} = \frac{\sum \frac{P_{NIP_{n-1}} + P_{NIP_n}}{2}(t_n - t_{n-1})}{1,000,000} A_{field}$$

where:

E_{field}	=	available energy incident on the heliostat field, MWht.
P_{NIP}	=	insolation based on measurements by the normal incident pyrheliometers, W/m². The readings of the two NIP meters are to be used along with the maintenance records to determine the insolation reading. The process for determining the most accurate reading is described in the Usable Energy section which follows.
A_{field}	=	total reflective area of the heliostat field, m².
t	=	time at which the insolation data is taken, hours.
n	=	counter for delineating one data sample from another.

Usable Energy

Since the Solar Two receiver has a design turndown ratio for the receiver of 20 percent based on an incident solar radiation level of 950 W/m², the usable daily energy is defined as that energy above 190 W/m².

Compute: WHEN $\frac{P_{NIP_{n-1}} + P_{NIP_n}}{2} \geq 190$ THEN

$$E_{usable} = \frac{\sum \left(\frac{P_{NIP_{n-1}} + P_{NIP_n}}{2} \right) (t_n - t_{n-1})}{1{,}000{,}000} A_{field}$$

where:

E_{usable} = usable energy incident on the heliostat field, MWht.

P_{NIP} = insolation based on measurements by the normal incident pyrheliometers, W/m². The readings of the two NIP meters are to be used along with the maintenance records to determine the insolation reading.

A_{field} = total reflective area of the heliostat field, m².

t = time at which the insolation data is taken, hours.

n = counter for delineating one data sample from another.

The process for determining the insolation reading is:

The average of the two insolation readings unless the two measurements differ by 25 W/m² or more. If the measurements differ by 25 W/m² or more, the reading which is within 25 W/m² of the clear sky insolation as predicted by the clear sky insolation model called out below will be selected, and the other normal incident pyrheliometer will be replaced or recalibrated immediately. If both readings are more than 25 W/m² from the clear sky insolation model prediction, the clear sky insolation model prediction will be used until the normal incident pyrheliometers are repaired or recalibrated.

The insolation readings will be compared against the clear sky insolation model prediction periodically to determine if maintenance procedures are being followed, or to determine if the pyrheliometers and their signal conditioning have suffered a common degradation in performance.

Clear Sky Insolation Model – There are several models for predicting the clear sky insolation as described in the DELSOL3 Manual by Kistler (SAND86-8018). The Allen model predicts the highest clear sky insolation and is the initial choice. During the Test and Evaluation year, the insolation readings will be compared against the Allen and other models. The model which best predicts the clear sky insolation will be selected for the Power Production Phase.

Energy Collected by the Receiver

$$E_{rec} = \sum \left\{ \frac{P_{rec_n} + P_{rec_{n-1}}}{2} \right\} (t_n - t_{n-1})$$

where:

E_{rec} = energy collected by the receiver, MWht.

P_{rec_n} = power collected by the receiver, MWt.

$$P_{rec_n} = FI5102_n * \left[cp(TI5366A_n) * TI5366A_n - cp(TI5104_n) * TI5104_n \right]$$
$$+ FI5302_n * \left[cp(TI5166A_n) * TI5166A_n - cp(TI5304_n) * TI5304_n \right]$$

where:

FI	=	mass flowrate, lbm/sec. Flowmeter data, delta pressure data, and receiver pump speed data will be compared to assure the best estimate of this flowrate.
cp	=	specific heat, Btu/lbm-°F. The specific heat of the salt will be computed by a subroutine using temperature curve fits.
TI	=	temperature, °F. The inlet and outlet temperature thermocouples should be calibrated weekly.
t	=	time at which the data is taken, hours.
n	=	counter for delineating one data sample from another.

The summation is to take place over the period of interest when the following conditions are met:

1. One or more receiver pumps have a speed above 0 rpm.
2. The downcomer drag valve, LV5022 or LV5023, is open.
3. The downcomer diversion valves are configured to pass salt to the hot tank as follows: valve TV5027A is open, and valve TV5027B is closed.

Gross Electrical Energy Production

There are two methods to arrive at this number. One is to read the station gross electric watt-hour meter every day at midnight and take the difference between successive readings. The other is to integrate the gross power as follows:

$$E_{gross} = \sum \left\{ \frac{JI5100_n + JI5100_{n-1}}{2} \right\} (t_n - t_{n-1})$$

where:

E_{gross}	=	gross electrical energy generated by the turbine, MWh_e.
$JI5100_n$	=	gross electrical power generated by the turbine, MW_e.
t	=	time at which the data is taken, hours.
n	=	counter for delineating one data sample from another.

Summations are to be totaled over the period of interest.

Net Electrical Energy Production

There are two methods to arrive at this number. One is to read the station gross electric and parasitic power watt-hour meter every day at midnight and take the difference between successive readings, and then subtract the parasitic energy from the gross energy. For the purposes of determining the plant net electrical power for the contractor performance award, the station watt-hour meter readings taken at midnight will be used.

The other method is to integrate the parasitic power as follows:

$$E_{parasitic} = \sum \left\{ \frac{JIX5001_n + JIX5001_{n-1}}{2} \right\} (t_n - t_{n-1})$$

where:

$E_{parasitic}$	=	parasitic electrical energy, MWh_e.
$JIX5001_n$	=	parasitic electrical power, MW_e.
t	=	time at which the data is taken, hours.
n	=	counter for delineating one data sample from another.

Summations are to be totaled over the period of interest. The net daily electrical energy, E_{net}, is computed as follows:

$$E_{net} = E_{gross} - E_{parasitic}$$

Thermal Energy in Hot and Cold Tanks at Midnight

Since the hot and cold tanks can store energy relative the 'zero' energy temperature of 550 °F, it is necessary to tabulate, at midnight, the energy carried over from 1 day to the next as follows

$$E_{tank_i} = \sum_{n=1}^{N} \rho_n c_{p_n} V_n (T_n - 550)$$

where:

E_{tank_i}	=	energy in the tank at time i.
ρn	=	effective density of tank contents, tank wall, and insulation associated with temperature T_n.
cpn	=	effective specific heat of tank contents, tank wall, and insulation associated with temperature T_n.
Vn	=	volume of tank associated with temperature T_n.
n	=	index for temperature measurement.
N	=	number of measured tank temperatures at time i.

This calculation is to be performed for both the hot and cold tank.

2. Sum and tabulate the daily energy values on a monthly and annual basis.

3. Compute key efficiencies as follows:

$$\text{Power Production Efficiency}_{\text{period}} = \frac{\text{Net Electrical Energy}_{\text{period}}}{\text{Useable Energy}_{\text{period}}}$$

$$\text{Collection Efficiency}_{\text{period}} = \frac{\text{Energy Collected by the Receiver}_{\text{period}}}{\text{Useable Energy}_{\text{period}}}$$

$$\text{Conversion Efficiency}_{\text{period}} = \frac{\text{Gross Electric Energy}_{\text{period}}}{\text{Energy Collected by Reciever}_{\text{period}} - \text{Hot Tank Energy}_{\text{period end}} - \text{Cold Tank Energy}_{\text{period end}}}$$

4. Review the following documents provided by the contractor to prepare equipment repair statistics, availability, and costs:

    Monthly Progress Report
    Monthly Operating Cost
    Monthly Maintenance Cost
    Monthly Plant Performance Report
    Daily Operators Log
    Daily Events Log
    Monthly Maintenance Log
    Monthly Heliostat Cleaning Log
    Monthly BCS Target and Heliostat Calibration Logs
    Monthly Equipment Status Logs
    Monthly Spare Parts Inventory Report
    Monthly Power Production Report

Deliverables:

1. Daily, monthly, and yearly plant performance tabulations showing the energies and efficiencies computed
2. System performance data in the form of the plant's daily output thermal energy collected, gross electric, and net electric versus the daily integrated insolation.
3. Monthly and yearly analysis of operating and maintenance costs and activities by labor category (electronic tech., operator, pipefitter …).
4. Review of equipment failures and repairs. Suggestions for alternative designs and installation methods.
5. Predictions of commercial-scale solar central receiver power plants annual energy output and operating and maintenance costs.

Acceptance Criteria:

Data determined valid based on review of calibration activities by maintenance, and review of plant data by data validation software.

Resources Required:

Pre-Test	–	One test engineer to prepare revised predictions based on results of Test 14
Test	–	Operations staff. Test engineer to visit site monthly.
Post-Test	–	One test engineer during power production to review data and prepare summaries and reports

1.16 Dispatchability

Test No.: 16 Dispatchability

Description: The plant is operated so that the stored heat is used to generate power, at levels lower than 10 MWe, for periods in excess of 3 hours, in particular for 6 hours.

Objectives:

1. Determine the capability of the plant to dispatch power for different periods.
2. Provide a matrix of average power produced for specific dispatch periods, noting related ambient weather conditions.
3. Dispatch stored heat at different times of the day and night, to identify effects on operating procedures and unexpected changes in plant efficiency.
4. Document the lessons-learned and recommend changes to design and operation, if applicable.

Prerequisites:

Preanalysis	–	None
Calibration	–	TBD
Plant Operating Status	–	Operational
Weather	–	Not applicable
Other	–	None

Precautions:

None

Test Sequence:

The nominal separation of the energy-collection and power production systems will have been demonstrated in previous tests. This test will demonstrate the flexibility of meeting a wide range of load-shifting requirements, for example, the equivalent of 6 hour storage by operating the power production system at derated conditions for the full 6 hours without energy collection.

An initial test sequence would cover a dispatch period of 6 hours. Operation of the power production system from the various overnight thermal-conditioning approaches, and power production prior to energy collection on morning start-up.

Data Requirements:

Key Instruments	–	None
Duration	–	6 weeks
Frequency	–	Not applicable
Other	–	None

Data Reduction:

Review data and compare to Test 15 results.

Deliverables:

1. All of Test 15 deliverables for the period of this test.
2. Demonstrated dispatchability.
3. Demonstrate operation of a plant with large solar multiples and storage capacity.

Acceptance Criteria:

Dispatchability is demonstrated.

Resources Required:

Pre-Test	–	None
Test	–	Operations staff. One test engineer for first week.
Post-Test	–	One test engineer for a month to review data and prepare report

1.17 Repeat of Key Efficiency and Performance Tests

Test No.: 17 Repeat of Key Efficiency and Performance Tests

Description: Repeat a reduced set of the receiver efficiency tests of Test 6, thermal loss tests of Test 8, and parasitic power tests of Test 9.

Objectives:

1. Repeat selected tests of Tests 6, 8, and 9.
2. Compare the results to those from Tests 5, 8, and 9, and conduct any other test indicated, including measuring the receiver's absorptivity, to explain the differences.
3. Conduct these tests following the first and second year of the power production phase.
4. Determine any degradation in the receiver's efficiency or performance.

Prerequisites:

Preanalysis – Results from Test 6, 8, and 9

Calibration – TE5104 – east inlet salt temperature
TE5166A and B – east outlet salt temperatures
TE5304 – west inlet salt temperature
TE5366A and B – west outlet salt temperatures
FT5102 – east salt flowrate
FT5302 – west salt flowrate

Measure heliostat field cleanliness every 3 days during test period. If precipitation or a dust storm occurs during the test period, remeasure field cleanliness directly after.

Measure receiver absorptivity within 3 months of test per receiver absorptivity measurement plan.

Plant Operating Status – Heliostat field at 90 percent or better availability with heliostat outages randomly scattered throughout the field. Heliostat field alignment verified by BCS within the last 6 months. Receiver system controls able to tolerate a 50 percent of max. power level change and damp response of receiver within 15 minutes. Turn off receiver loop heat tracing for power-off testing.

Weather – Clear day. Peak insolation predicted to be 800 W/m^2 or more. Wind below 5 mph for one set of tests, wind between 10 and 20 mph for second set of tests. For Phase IV testing (during power production), the test day weather should be similar to one of the Phase II weather conditions.

Other – None

Precautions:

1. Limit rate at which heliostats can be placed back on the receiver so as not to exceed receiver control capability.

2. Care must be exercised when performing power-off testing at 700 °F not to exceed the minimum level in the cold tank so that after testing, cold salt may be added to lower the salt temperature. This is due to receiver inlet temperature limitations during high insolation periods.
3. Assess tests performed during windy conditions to insure a high enough salt flow to preclude freezing in the receiver.

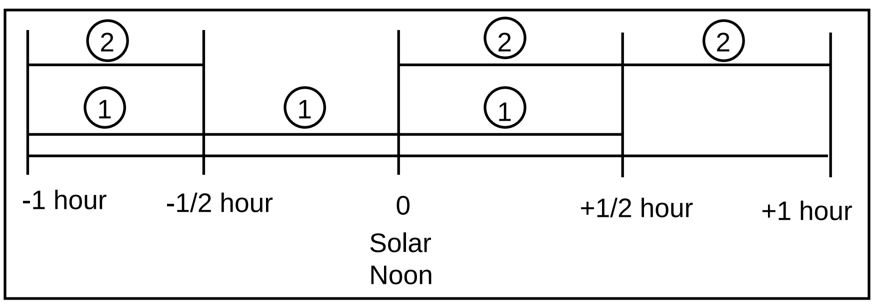
Test Sequence:

Power Off Testing

Testing at 550 °F: Flow cold salt at 550 °F ±20 °F through the receiver with no heliostats tracking the receiver. Cold salt returned to cold salt tank. Measure the temperature drop across the east and west string of panels. Receiver loop heat tracing is turned off.

Power On Testing:

1. Place receiver in steady-state operation with full field (sets 1 and 2) with a receiver outlet temperature of 1,050 °F ±25 °F.
2. At 1/2 hour before solar noon, command set 2 of heliostats to standby.
3. At solar noon, command set 2 of heliostats back on track.
4. At 1/2 hour after solar noon, command set 1 of heliostats to standby.
5. At 1 hour after solar noon, command set 2 of heliostats to track. Test is complete. Normal operations may resume.



Tracking Sequence of Complementary Groups of Heliostats

Thermal Losses

1. Review plant data from DAS for hold periods where thermal loss data can be extracted.
2. Repeat the IR Survey and analyze video tape

Parasitic Power

Review plant data from DAS and examine plant states and transitions for changes in parasitic power consumption

Data Requirements:

Key Instruments	–	None
Duration	–	Two to four test days.
Frequency	–	Not applicable

Data Reduction:

Reference Tests 6, 8, and 9.

Deliverables:

1. Comparison of receiver efficiency to previous test results.
2. Comparison of plant thermal losses to previous test results.
3. Comparison of plant parasitic power consumption to previous test results.
4. Recommendations for plant modifications to correct defective insulation.
5. Recommendations on how to reduce parasitic power.
6. Recommendation on whether to repaint the receiver.

Acceptance Criterion:

Completion of receiver efficiency tests and data evaluation.

Resources Required:

Pre-Test	–	One test engineer to review previous results
Test	–	One test engineer and operations staff
Post-Test	–	One test engineer

1.18 Coupon Corrosion and Salt Chemistry

Test No.:18 Coupon Corrosion and Salt Chemistry

Description: There are two categories of tests:

(1) Periodic removal of salt samples from the receiver pump sump to monitor changes in chemical composition of the salt during plant operation.

(2) Immersion of corrosion coupons at selected locations in the molten salt loop and removal at yearly intervals for metallographic and weight-loss analysis. Exposure locations and equipment numbers of the test chambers consist of chamber Y-850 in the steam generator pump sump (V-850), chamber Y-250 in the receiver pump sump (V-250), chamber Y-851 in interconnecting piping line NS037 between the evaporator mixer (MI-851) and evaporator (E-852), and chamber Y-251 in the receiver downcomer line NS012.

Objectives:

(1) Determine effects of extended solar operation on salt chemical composition.

(2a) Measure corrosion behavior of baseline and alternate salt loop containment materials under solar service conditions. Exposure locations represent continuous isothermal hot salt exposure (Y-850), continuous isothermal cold salt exposure (Y-250), thermal cycling exposure at evaporator inlet (Y-851), and thermal cycling plus fill-and-drain of the receiver (Y-251).

(2b) Determine effects of commercial-grade salt and service-related changes in salt chemical composition on corrosion behavior.

Prerequisites:

Calibration	–	Thermocouples TE 5024, 5050, 5744 and 5779 should be calibrated and operational at all times, to maintain a record of operating temperature near each of the four test chambers.
Plant Operating Status	–	Plant must be in long term hold for safe removal of coupons and salt samples
Weather	–	Not applicable
Other	–	None

Precautions:

Procedures for safe removal of corrosion coupons and salt samples. Salt sampling and coupon retrieval from sump chambers Y-250 and Y-850 will typically occur while sumps are filled with hot salt, but pumps are not operating. Caution must be exercised during the removal procedure, since coupons and fixtures will initially be at the sump operating temperature, 550 °F and 1,050 °F, respectively. Coupon retrieval from piping chambers Y-251 and Y-851 must occur during plant shutdown, with affected salt piping lines drained and heat tracing near the chambers turned off. Caution must be exercised during retrieval if piping near the chamber has not cooled to ambient.

Test Sequence:

Salt Chemistry

At prescribed intervals, salt samples are removed from the pump sumps during plant shutdown or standby operation. Access for salt sampling is obtained by removing the blind flange that covers the spare nozzles used for the sump corrosion chambers, Y-250 and Y-850. Note safety precautions regarding high temperatures involved. A ladle is lowered down the inside of the corrosion chamber to obtain a minimum 20 gram salt sample. The molten salt is poured from the ladle onto a stainless steel sheet to cool, and the solidified salt flakes are then collected in an inert sample container that is sent for chemical analysis.

Chemical analysis of samples is performed to determine changes in composition resulting from plant operation, including the effects of prolonged time at elevated temperature, prolonged exposure to the atmosphere, and the presence of dissolved products of corrosion of containment materials in the salt loop. Chemical analysis includes, at a minimum, the following species: nitrite, chloride (perchlorate), carbonate, free oxide (hydroxide), and total dissolved chromium. Samples are taken at the following intervals:

- An initial zero-time sample is removed from both the receiver pump sump (V-250) and the steam generator pump sump (V-850) upon completion of salt melting, at the same time as corrosion specimens are loaded in the sump corrosion chambers (Y-250 and Y-850, respectively).
- Samples are removed from both sumps (V-250 and V-850) at approximately monthly intervals for the first 6 months after the initial sample. If there is no significant difference between samples from each sump, salt samples after the first 6 months are taken only from the receiver pump sump (V-250).
- A salt sample is taken from the receiver pump sump at approximately 9 months.
- A salt sample is taken from the receiver pump sump at approximately 12 months after the initial sample, and at every 6 months thereafter for the duration of Solar Two operation.

Coupon Corrosion

Chambers for coupon exposure are incorporated in salt loop construction. Coupons mounted on specimen fixtures are inserted in test chambers at different times, but in all cases prior to plant start-up and checkout. Corrosion coupons are inserted in chambers Y-251 and Y-851 when the chambers are constructed and welded into the salt loop piping, and thus are present in the salt loop prior to salt loading and melting. Corrosion coupons are inserted in the sump chambers, Y-250 and Y-850, only after salt melting is complete.

Multiple sets of coupons are provided at each exposure location and remain exposed to molten salt throughout plant operation. Specimen fixtures are retreived approximately yearly during normal plant shut-down. At this time, one coupon set from each location is removed from its fixture for analysis, and the fixtures with remaining coupons attached are returned to their exposure locations. Coupons removed for analysis are not returned to the salt loop for further exposure. Metallographic and weight-change analyses are performed on removed coupons to determine long-term corrosion behavior under plant operating conditions. Procedures for coupon retrieval and analysis are as follows:

Retrieval procedures for coupons from salt piping chambers Y-251 and Y-851:

- Remove insulation and bend heat tracing lines as needed to expose chamber end cap. Note precautions regarding possible high temperatures.
- Cut end cap from chamber body at original cap-to-body weld, leaving a cut surface suitable for later rewelding. Remove end cap, pulling attached specimen fixture from the chamber body.
- Remove coupons corresponding to the current removal interval, after using hot water to clean residual salt from fixture and attached coupons.
- To prevent molten salt contamination of new cap-to-body weld, clean residual solidified salt from inside of chamber body and cap in areas likely to be affected by weld heat input. Prepare cut edges of cap and body for rewelding.
- Reinsert cap with attached coupon fixture, taking care to assure that the cap/fixture maintained for proper draining of the chamber and to prevent coupons and fixtures from becoming locked in residual solidified salt at the next removal interval.
- Reweld end cap to chamber body and perform required NDE per approved salt piping weld procedures. Replace heat tracing and insulation.

Retrieval procedures for coupons from pump sump chambers Y-250 and Y-850:

- Unbolt and remove blind flange covering chamber, and withdraw specimen fixture suspended at the end of chain attached to flange. To facilitate coupon removal, fixture may be separated from chain by cutting a chain link, and then reattached to chain with a threaded chain link prior to reinserting in the test chamber.
- Remove coupons corresponding to the current removal interval, then return fixture with remaining coupons to the chamber. Note that specimen removal would also typically coincide with a periodic required salt sample, which would be obtained at this time.
- Replace and rebolt blind flange.

Analysis of corrosion coupons:

- Coupons for each removal interval are typically in sets of three for each alloy, two of which are used for weight change measurement and one used for metallographic examination. Other samples used only for metallography exist as singles or duplicates.
- All coupons retrieved for analysis are initially washed in hot water to remove any adhering salt, then weighed to determine weight change with oxide scales intact.
- Coupons used for weight change measurement are then chemically descaled, and reweighed to determine weight change of remaining base metal.

- Coupons for metallography are not descaled. Coupons are cross-sectioned, mounted in epoxy, polished, and examined metallographically. Some coupons may be nickel plated prior to sectioning to assure retention of oxide scales.

Data Requirements:

Key Instruments – Thermocouples for logging temperature history near coupon corrosion test locations, consisting of:
TE 5744 for steam generator pump sump chamber Y-850
TE 5050 for receiver pump sump chamber Y-250
TE 5779 for superheater-to-evaporator piping chamber Y-851
TE 5024 for receiver downcomer chamber Y-251

Frequency – Not applicable

Duration – Continuous during plant start-up and operation as part of normal data acquisition

Data Reduction:

Metallographic and weight-loss analysis of corrosion coupons.

Salt temperature history for coupon corrosion locations.

Analysis of salt chemical composition versus plant operating history.

Deliverables:

Periodic updates and final report on changes in salt chemical composition as a function of plant operating time.

Yearly updates and final report characterizing the type and extent of corrosion experienced by salt loop containment materials during operation of Solar Two, including comparison of results of Solar Two exposure with results from corresponding previous laboratory corrosion experiments.

Updated summary recommendations on procurement specifications and in-service control of salt chemical composition for commercial central receiver systems.

Updated summary recommendations on molten salt containment materials specifications, applications, and corrosion allowances for commercial central receiver systems.

Acceptance Criterion:

Samples obtained and evaluated per Test No. 18.

Resources Required:

Pre-Test – Test engineer to verify thermocouple calibration, and insert coupons in sump chambers.

Test – Test engineer to oversee periodic salt sampling and removal/replacement of corrosion coupons, including coordination of removal schedule with operations staff. Corrosion engineer for ongoing analysis of salt chemistry and coupon corrosion samples.

Post-Test – Test engineer, corrosion engineer.

Interface Requirements on the O&M Contractor.

Removal (cutting) and reinstallation (welding) of piping chambers Y-251 and Y-851.

1.19 Storage Tank Thermal Stresses

Test No.: 19 Storage Tank Thermal Stresses

Description: Measure the stresses in the hot nitrate salt storage tank walls as a function of initial fill and fill rate.

Objectives:

1. Obtain temperature and strain gage data for assessing the stresses in the walls and bottom joints of the storage tanks under transient conditions.
2. Measure the initial strains and movement of the tank due to heating and fill.

Prerequisites:

Preanalysis	–	Predicted stresses in storage tanks by finite code. Ready by mid-July 1995.
Calibration	–	Special data acquisition system attached to tank, calibrated and functional
Plant Operating Status	–	Normal plant availability and mirror cleanliness
Weather	–	Clear sunny, high insolation day for level changes
Other	–	None

Precautions:

TBD

Test Sequence:

Three tests are proposed:

1. **Hot Tank Heel** – Hot tank is at its minimum level. Wait until midday of a clear, high isolation day, before starting the receiver. Flow hot salt into the hot tank at the maximum rate. Record temperature and strains.
2. **Level Changes** – During normal midday operations when hot salt flows are at or within 10 percent of maximum, record tank wall temperatures and strains.
3. **Initial Tank Warm-Up and Fill** – Monitor movement and growth of the tank with respect to reference points on the foundation.

Data Requirements:

Key Instruments	–	Record plant data per Data Acquisition System Data Base. Special data acquisition system attached to tank under test.
Duration	–	4 hours each test
Frequency	–	One sample per minute
Other	–	Note weather conditions during measurement

Data Reduction:

Comparison of temperatures and strains to prediction by finite element code.

Deliverables:

1. Tank wall and bottom joint temperatures and strains.
2. Evaluation of Solar Two tank design and the implications for a commercial scale plant.

Acceptance Criteria:

Data are obtained before and during tank filling.

Resources Required:

Pre-Test	–	Test engineer and instrument technician to connect portable data acquisition system to storage tank instrumentation. Structural engineer, finite element code, main-frame computer to prepare predictions.
Test	–	Test engineer
Post-Test	–	Test engineer and technician remove portable data acquisition system. Structures engineer, finite element code, main-frame computer.

1.20 Extended Operational Tests

Test No: 20 Extended Operational Tests

Description:

1. Extended operational tests may be conducted to either incorporate and test product improvements identified during the engineering test and evaluation phase or to further improve and demonstrate the performance of Solar Two as configured.
2. These tests are beyond the scope of the initial test and operation program, and are not budgeted. As the Test and Evaluation Phase progresses, ideas for extended testing will find their way to this test in successive updates. Once defined, funding will be sought during the Power Production Phase.

Objectives:

1. Testing of product improvements to this system.
2. Additional data to support the development of this technology.

Prerequisites:

Calibration – TBD

Plant Operating Status – TBD

Weather – TBD

Other – TBD

Precautions:

TBD

Test Sequence:

TBD

Data Requirement:

Key Instruments – TBD

Duration – TBD

Frequency – TBD

Data Reduction:

TBD

Deliverables:

TBD

Acceptance Criterion:

TBD

Resources Required:

Pre-Test	–	TBD
Test	–	TBD
Post-Test	–	TBD

1.21 Post-Test Examination

Test No.: 21 Post-Test Examination

Description: Perform special one-time tests at the end of the Power Production Phase.

Objectives:

1. Collect data to aid in receiver and steam generator lifetime predictions.
2. Extend database on maintenance activities.
3. Determine the factor of safety for receiver operations.

Prerequisites:

Calibration	–	TBD
Plant Operating Status	–	Power production phase and Test 21 complete
Weather	–	TBD
Other	–	TBD

Precautions:

TBD

Test Sequence:

The intent of this test plan is to encapsulate all of the tests of value which might be conducted after formal operations of Solar Two are complete. Due to the preliminary nature of these plans, specific procedures are not possible. Therefore, a discussion of the rationale for the test and the work involved will be presented in this section. When budget becomes available, one or more of the following tests could be detailed and carried out.

Cold-Start the Receiver

This test investigates whether the receiver can be filled when it is essentially at ambient temperature without freezing salt or damaging the tubes/piping.

1. Heat trace all piping and headers to 550 °F.
2. Begin salt recirculation to insure no cold spots exist.
3. Place warm-up heliostats on the receiver.
4. Fill the receiver.

Test Receiver to Extremes

During the 3 year Test and Evaluation period, the receiver may not undergo all of the extremes possible to incur upon the receiver. As a result, the margin of safety under certain conditions may not be well understood and, therefore, remain as a troubling uncertainty to a potential investor or future receiver designer. A few examples of extremes are:

a. Overheating of a receiver panel.
b. Failure of selected portions of the receiver controller.

Sample Removal from Receiver and Steam Generator

Metal coupons will be installed in the plant piping during construction. Individual coupons will be removed at intervals and assessed for corrosion effects. The actual metal of the receiver and steam generator may undergo quite different thermal environments and will be subject to stress, something the coupons will not see. Therefore, metal samples may be cut out from the receiver and steam generator to study the differences, if any, in the corrosion rates at those locations. Some sample locations are:

a. Tube to header joint on the outlet header of the last panel of each flow circuit (panels E12 and W12).
b. Superheater tubing.
c. Edge tubes on the northeast and northwest panels (e.g., panels E3 and W3).
d. Locations in the receiver which repeatedly exceeded the design limits for temperature and temperature ramp rate.

Selected Maintenance Activities

Some major maintenance activities may not occur during regular operation. Therefore some of the following procedures may be performed to determine their difficulty, and to verify the repair procedure and time estimate:

a. Replace a receiver panel.
b. Overnight tube replacement.
c. Drain, cool, then reheat and fill a storage tank (leak repair simulation).
d. Replace a cold salt pump.
e. Thaw salt frozen in tubes in the receiver.
f. Thaw salt frozen in tubes in the preheater

Data Requirement:

Key Instruments – TBD

Duration – TBD

Frequency – TBD

Data Reduction:

TBD

Deliverables:

TBD

Acceptance Criterion:

TBD

Resources Required:

Pre-Test	–	TBD
Test	–	TBD
Post-Test	–	TBD

2.0 Evaluations

2.1 Efficiency and Energy Output

The objectives of this evaluation are:

1. Compare plant and system efficiency and energy throughput to prediction and recommend changes in plant operation and equipment, or revisions to the computer code for prediction in order that actual plant performance and predicted performance match within a tolerance of 10 percent or less on a monthly basis, and 5 percent or less on an annual basis.
2. Suggest means for improving energy efficiency.
3. Identify design and operation/maintenance changes which will improve the efficiency of a commercial scale plant.

The plant and system efficiencies will be presented in what is called daily input/output charts a Waterfall Chart. The basic calculations are defined in the data reduction section of Test 15, Power Production.

The T&E Team will compare the plant output with predicted output from an energy calculating program, such as SOLERGY, using the recorded values of solar radiation. Differences greater than 10 percent on a monthly basis, or 5 percent on a yearly basis, will trigger an investigation by the T&E Team to determine the root cause, which may be based in Solar Two or in the computer code, and to recommend changes to correct the situation.

Many of the recommended changes will be applicable to a commercial scale plant. Each recommended changes will be evaluated against the Solar 100 design to assess its potential impact on Solar 100 performance. A report will list the recommendations along with their expected impacts.

2.2 Parasitics and Losses Evaluations

The objectives of this evaluation are:

1. Compare the predicted thermal losses and electrical parasitics with measured values.
2. Suggest means to decrease the parasitic power consumption and reduce thermal losses.

Parasitic power consumption of major pieces of equipment will be measured continuously with plant instrumentation, or sporadically using portable, temporarily installed instrumentation as part of Test 9. Devices or systems with permanently mounted power instrumentation is called out in Table 7b.1. Parasitic power and thermal losses related to overnight thermal conditioning is conducted in Test 13. Thermal losses in the piping system will be evaluated using an IR camera in Test 8.

The reduced data from the above test series will be reviewed by the T&E Team which will recommend cost effective changes in operation or equipment for decreasing parasitic power and thermal losses.

Many of the recommended changes will be applicable to a commercial scale plant. Each recommended change will be evaluated against the Solar 100 design to assess its potential impact on Solar 100 performance. A report will list the recommendations along with their expected impacts.

Table 2-1. Components, Subsystem, or Systems for Which the Electrical Power Consumption Will be Monitored

Cold Tank Heat Tracing	Steam Generator Pump 1
Cold Salt Sump Heat Tracing	Steam Generator Pump 2
Receiver Pump 1	Hot Salt Sump Heat Tracing
Receiver Pump 2	Steam Generator Heat Tracing
Steam Generator Attemperation Pump	Cooling Tower
Riser Heat Tracing	Heliostat Field
Receiver Heat Tracing	Steam Generator Feedpump
Downcomer Heat Tracing	Lighting and Air Conditioning
Hot Salt Tank Heat Tracing	

2.3 Availability and Forced Outage Rate

The objectives of this evaluation are:

1. Calculate the typical electric utility industry plant availability parameters for Solar Two for daily, monthly, and annual periods.
2. Identify the causes of forced outages and other downtime and determine how these causes and associated loss of production could be reduced for Solar Two and commercial plants.
3. Recommend a method of determining plant availability suitable for molten salt, central receiver, and solar power plants.

Approach

The T&E Team will follow the methodology described in the Data Reporting Instructions for the Generating Availability Data System (GADS) published by the North American Electric Reliability Council (NERC) to calculate the various availability parameters. The basic GADS formulas for calculating availability parameters are provided on pages attached to this section, with definitions for the various factors. The diurnal operation of solar plants and the variability of fuel supply, requires additional consideration as described later in this section. Data for the calculations will be obtained from plant measurements as defined below, and from the computerized maintenance management system provided by the O&M Contractor.

There are two basic types of outage, planned and unplanned. Planned outages are for maintenance and overhauls. Unplanned outages are the result of equipment unreliability, environmental impact, regulatory restraints, and human error. At Solar Two, the loss of insolation to the collector field is an unplanned outage and will be separately recorded. For both types of outages, the minimum data to be recorded are as follows:

- System and component affected

- Reason for the outage
- Start and end of the outage in absolute time, and elapsed time
- Reduction in available generating capacity
- Man-hours required to maintain/repair.

Additional data collected for unplanned outages will include, at a minimum, the following:

- Failure description and appearance of component/equipment
- Cause of immediate failure and contributing factors
- Corrective actions
- Failure mechanism
- Trip mechanism.

A format will be provided for recording the required data.

The determination of plant availability is straightforward and, at most plants, it is done manually. The approach is to accumulate the amount of energy lost over the period of interest as a ratio of the energy that would have been generated if the plant had operated without downtime, and subtract that ratio from one. The factors of most interest are **Availability**, **Equivalent Availability**, and **Equivalent Forced Outage Rate**. The term "equivalent" refers to the normalization of hours to the net maximum capacity, e.g., 6 hours at 50 percent operation is 3 equivalent hours.

Solar or Operational Availability

In order to fulfill the objectives of Solar Two to determine the feasibility of commercial operation of central receiver solar plants, it will be necessary to calculate plant availability factors that are meaningful in the context of solar-thermal concepts. Specifically, many of the plant's systems cannot be used overnight or when insolation levels are lower than the design threshold. Planned plant maintenance will be performed during those periods. There might be other, more spontaneous, opportunities to perform maintenance during cloudy days. The demonstration of plant availability will not be unfairly penalized if systems are not available for operation when insolation levels are below the design threshold.

Another concern to be addressed is the availability of systems that are not operationally limited by insolation levels. A case in point is the availability of the EPGS when thermal storage is loaded. Because dispatchability of power from stored hot salt is one of the design features of Solar Two and potentially, future plants, it will be necessary for the O&M Contractor's records to capture equipment failure during low insolation levels and the quantity of hot salt stored at all times. The maximum storage capability of Solar Two is 3 hours at rated power, therefore, the availability of the EPGS system for 3 hours after sundown will be included in the calculation of availability.

O&M Contract's Availability Factor for Incentive Award Evaluation

For the purpose of calculating the "Availability Factor" for the O&M Contractor's incentive award, the determination will be based on the GADS definition of Equivalent Availability, modified by the insolation levels. To achieve a 100 percent availability, the plant must be fully operational with ALL systems capable of maximum design operation when the insolation levels are above the threshold (provisionally 190 w/m^2). For this purpose, no distinction will be made if the insolation level is too low to generate rated power or the plant is not warmed-up and thermally ready for salt flow to the receiver or steam to the turbine, or similar conditions. The equipment must be fully operational during the periods the insolation level thresholds are exceeded. Those insolation levels will be confirmed during the first year of plant operation that is when the T&E plan is being implemented.

Definitions

Appendix II

Time

Available Hours (AH)
Sum of all Service Hours (SH), Reserve Shutdown Hours (RSH), Pumping Hours, and Synchronous Condensing Hours, or,

Period Hours (PH) less Planned Outage Hours (POH), Forced Outage Hours (FOH), and Maintenance Outage Hours (MOH).

Equivalent Forced Derated Hours (EFDH)*
The product of Forced Derated Hours (FDH) and Size of Reduction, divided by Net Maximum Capacity (NMC).

Equivalent Forced Derated Hours During Reserve Shutdowns (EFDHRS)*
The product of Forced Derated Hours (FDH) (during Reserve Shutdowns (RS) only) and Size of Reduction, divided by Net Maximum Capacity (NMC).

Equivalent Planned Derated Hours (EPDH)*
The product of Planned Derated Hours (PDH) and Size of Reduction, divided by Net Maximum Capacity (NMC).

Equivalent Scheduled Derated Hours (ESDH)*
The product of Scheduled Derated Hours (SDH) and Size of Reduction, divided by Net Maximum Capacity (NMC).

Equivalent Seasonal Derated Hours (ESEDH)*
Net Maximum Capacity (NMC) less Net Dependable Capacity (NDC), multiplied by Available Hours (AH) and divided by net Maximum Capacity (NMC).

Equivalent Unplanned Derated Hours (EUDH)*
The product of Unplanned Derated Hours (UDH) and Size of Reduction, divided by net Maximum Capacity (NMC).

Forced Derated Hours (FDH)
Sum of all hours experienced during Forced Deratings (D1, D2, D3).

Forced Outage Hours (FOH)
Sum of all hours experienced during Forced Outages (U1, U2, U3, SF).

Maintenance Derated Hours (MDH)
Sum of all hours experienced during Maintenance Deratings (D4) and Scheduled Derating Extensions (DE) of any Maintenance Deratings (D4).

Maintenance Outage Hours (MOH)
Sum of all hours experienced during Maintenance Outages (MO and Maintenance Outage Extensions (SE of MO).

Period Hours (PH)
Number of hours a unit was in the active state. A unit generally enters the active state on its service date.

Planned Derated Hours (PDH)
Sum of all hours experienced during Planned Deratings (PD) and Scheduled Derating Extensions (DE) of any Planned Deratings (PD).

Planned Outage Hours (POH)
Sum of all hours experienced during Planned Outages (PO) and Planned outage Extensions (SE of PO).

Pumping Hours
The total number of hours a turbine/generator unit was operated as a pump/motor set (for hydro and pumped storage units only).

* Equivalent hours are computed for each derating and then summed.
Size of Reduction is determined by subtracting the Net Available Capacity (NAC) from the Net Dependable Capacity (NDC). In cases of multiple deratings, the size of Reduction of each derating is the difference in the Net Available Capacity of the unit prior to the initiation of the derating and the reported Net Available Capacity as a result of the derating.

Definitions

Appendix II (cont)

Time (cont)

Reserve Shutdown Hours (RSH)
Total number of hours the unit was available for service but not electrically connected to the transmission system for economic reasons.

Some classes of units, such as gas turbines and jet engines, are not required to report Reserve Shutdown (RS) events. If not reported, Reserve Shutdown Hours (RSH) for these units are computed by subtracting the reported Service Hours (SH), Pumping Hours, Synchronous Condensing Hours, and all the outage hours, from the Period Hours (PH).

Scheduled Derated Hours (SDH)
Sum of all hours experienced during Planned Deratings (PD), Maintenance Deratings (D4) and Scheduled Derating Extensions (DE) of any Maintenance Deratings (D4) and Planned Deratings (PD).

Scheduled Outage Extension Hours
Sum of all hours experienced during Scheduled Outage Extensions (SE) of any Maintenance Outages (MO) and Planned Outages (PO).

Scheduled Outage Hours (SOH)
Sum of all hours experienced during Planned Outages (PO), Maintenance Outages (MO), and Scheduled Outage Extensions (SE) of any Maintenance Outages (MO) and Planned Outages (PO).

Service Hours (SH)
Total number of hours a unit was electrically connected to the transmission system.

Synchronous Condensing Hours
Total number of hours a unit was operated in the synchronous condensing mode.

Available Hours (UH)
Sum of all Forced Outage Hours (FOH), Maintenance Outage Hours (MOH), and Planned Outage Hours (POH).

Unplanned Derated Hours (UDH)
Sum of all hours experienced during Forced Deratings (D1, D2, D3), Maintenance Deratings (D4), and Scheduled Derating Extensions (DE) of any Maintenance Deratings (D4).

Unplanned Outage Hours (UOH)
Sum of all hours experienced during Forced Outages (U1, U2, U3, SF), Maintenance Outages (MO), and Scheduled Outage Extensions (SE) of any Maintenance Outages (MO).

Capacity and Energy

Gross Actual Generation (GAG)
Actual number of electrical megawatthours generated by the unit during the period being considered.

Gross Available Capacity (GAC)
Greatest capacity (MW) at which a unit can operate with a reduction imposed by a derating.

Gross Dependable Capacity (GDC)
GMC modified for seasonal limitations over a specified period of time.

Gross Maximum Capacity (GMC)
Maximum capacity (MW) a unit can sustain over a specified period of time when not restricted by seasonal or other deratings.

Net Actual Generation (NAG)
Actual number of electrical megawatthours generated by the unit during the period being considered less any generation (MWh) utilized for that unit's station service or auxiliaries.

Net Availability Capacity (NAC)
GAC less the unit capacity (MW) utilized for that unit's station service or auxiliaries.

Net Dependable Capacity (NDC)
GDC less the unit capacity (MW) utilized for that unit's station service or auxiliaries.

Net Maximum Capacity (NMC)
GMC less the unit capacity (MW utilized for that unit's station service or auxiliaries.

Equation

Appendix III

Age
[Years in commercial service/Number of units]

Availability Factor (AF)
[AH/.PH] x 100 (%)

Average Run Time (ART)
[SH/Actual Unit Starts]

Equivalent Availability Factor (EAF)
[(AH-{EUDH + EPDH + ESEDH))/PH] x 100(%)

Equivalent Forced Outage Rate (EFOR)
[(FOH + EFDH)/(FOH + SH + EFDHRS)] x 100(%)

Forced Outage Factor (FOF)
[FOH/PH] x 100 (%) [SH/PH] x 100 (%)

Forced Outage Rate (FOR)
[FOH/(FOH + SH) x 100 (%)

Gross Capacity Factor (GCF)
[GAG/PH x GMC] x 100(%)

Gross Output Factor (GOF)
[GAG/SF x GMC] x 100 (%)

Net Capacity Factor (NCF)
[NAG/(PH x NMC) x 100 (%)

Net Output Factor (NOF)
[NAG/(SH x NMC}] x 100 (%)

Scheduled Outage Factor (SOF)
[SOH/PH] x 100 (%)

Service Factor (SF)
[SOH/PH] x 100 (%)

Starting Reliability (SR)
[Actual Unit Starts/Attempted Units Starts] x 100 (%)

Average Number of Occurrences Per Unit-Year

$$\text{AVG NO OCC PER UNIT-YR} = \frac{\Sigma \text{ Outage and/or Derating Occurrences}}{\text{Unit-Years}}$$

Average MWh Per Unit-Year

$$\text{AVG MWh PER UNIT-YR} = \frac{\Sigma\text{Hours for Each Outage and/or Derating Type x NMC (MW)}}{\text{Unit-Years}}$$

Average MWh Per Outage

$$\text{AVG MW PER OUTAGE} = \frac{\Sigma \text{ Hours for Each Outage and/or Derating Type x NMC (MW)}}{\text{Occurrences}}$$

Average Hours Per Unit-Year

$$\text{AVG MWh PER UNIT-YR} = \frac{\Sigma\text{Hours for Each Outage and/or Derating Type x NMC (MW)}}{\text{Unit-Years}}$$

Average Equivalent Hours Per Unit-Year
Computed the same way as **Average Hours per Unit-Year** shown above, except deratings are converted equivalent full outage hours. Equivalent hours are computed for each derating event experienced by each unit. These equivalent hours are then summarized and used in the numerator of the **Average Hours Per Unit-Year** equation.

2.4 Operability and Controllability

The objectives of this evaluation are:

1. Maximize the operating time of Solar Two by optimizing the plant controls for transitions.
2. Minimize the thermal cycling of Solar Two equipment.
3. Determine the effect of extreme weather conditions on the operability of Solar Two.
4. Demonstrate the dispatchability of a solar central receiver.
5. Extrapolate the lessons learned to a 100 MWe or larger solar central receiver.

Since the most difficult control problems are associated with the receiver and heliostat field, they are the object of the majority of tests and evaluations. Test 5, Heliostat Patterns for Receiver Warm-up, and Test 12, Optimization of Receiver Loop Operations, address transition control. Tests 5, 10, 11, and 12 address the influence of extreme weather conditions on receiver control. Test 16 will explore dispatchability.

The approach is to observe plant operation during transitions and compare the time required for the transitions to the time predicted. If the time taken is more than 10 percent longer than predicted, the root cause for the slowness of the transition will be sought, and control or design modifications will be suggested. If all transitions are within 10 percent of predicted times, then the T&E Team will review transitions for possible improvements.

With respect to cloud transients, the T&E Team will review the data to determine the most energy efficient logic for determining whether to keep the receiver filled while waiting for the sun to return.

Many of the recommended changes will be applicable to a commercial scale plant. Each recommended changes will be evaluated against the Solar 100 design to assess its potential impact on Solar 100 performance. A report will list the recommendations along with their expected impacts.

2.5 Maintenance and Maintainability

For the T&E Team, the objectives of this evaluation are:

1. Acquire and reduce data to failure and maintenance statistics.
2. Determine the appropriate level of effort which cost-effectively minimizes plant unavailability.
3. Evaluate the equipment layout for ease of access.
4. Identify changes to maintenance practices, equipment selection, or design that would improve maintenance activities.

Maintenance Activities Data – In order to estimate the O&M costs for Solar 100, the T&E team will have access to O&M information for Solar Two then extrapolate that data to predict similar costs for future plants. The scope of work for the O&M Contractor requires a computerized maintenance management system. The T&E Team will either have access to that system or be given a data dump on magnetic storage media so that they can perform data reduction and analysis.

At a minimum, maintenance data will include identification of the component and system, a brief description of the problem and the solution or repair, job hours and personnel skills expended on repair, components and consumables used, plant downtime and lost power/energy. Scheduled maintenance, including mirror washing, valve seal replacement, etc., will be similarly reported. All maintenance activities and failure data will be recorded by the operators and maintainers in the computer database.

The level of detail must be sufficient to enable the T&E Team to develop statistical results by components, subsystems, skill levels, lost power/energy, absolute time, and insolation levels. The recorded O&M data will be analyzed by the T&E Team to provide frequency of failure, mean-time-between-failure (MTBF) and mean-time-to-repair (MTTR) for major components and, also, to identify components with long or frequent downtime. See also Section 2.3, **Availability Parameters** for additional data and reporting requirements.

Failure causes will be reviewed by the T&E team, with assistance from the O&M Contractor, to identify and categorize design inadequacies, operator or maintainer errors (human interface design problems), installation errors, location problems, and common cause failures.

Maintenance requirements of the plant will be determined from records of plant failures, repair activities, spare parts used, and other consumables. In particular, the O&M Contractor shall record in the database, the on-site and support staff, their skill levels, hours on-the-job (regular and overtime), and labor rates. It is important that a breakdown of time and skill levels is provided so that other rates and shift schedules can be explored for future plants operating under different labor costs and conditions.

Resolution of Chronic Maintenance Problems – In cases of standard design components that cause long outages or require much maintenance, the T&E Team will compare the component maintenance and failure rates with records of similar components from the Participants' generating plants to identify solutions.

Operator's Daily Log – The Operator's Daily Log will be provided by the O&M Contractor and will be similar in concept to the example from SEGS IV plant, as shown in Figure 2.5-1. In general, plant performance will be tracked by storing data on such parameters as total day's direct normal insolation, thermal energy collected, gross and net energy produced, station load, total parasitics, thermal conditioning loads and daily change in the amount of energy in storage (typically zero). Absolute time references will be given to any scheduled or unscheduled outages. The final format will be developed by mutual agreement between the Edison and the O&M Contractor.

Plant Performance Report – This will be a monthly document provided by the O&M Contractor that summarizes the performance, efficiency, availability and maintainability of the plant, and provides a tabulation of the daily values of the data recorded on the Operator's Daily Log. The purpose of the document is to provide a running-record of plant status, and O&M experience. The data presented will summarize the data from the Operator's Daily Log and the current month's entries to the Maintenance Database. Typical data to be provided in the monthly Plant

Performance Report will include spare parts use and inventory levels, changes to plant design and O&M procedures. Estimates of the benefits associated with all changes should also be reported and supported as feasible. Changes that were tested but proved to be unsatisfactory and the reasons for their rejection will be provided. A preliminary report format will be mutually agreed to by the O&M Contractor and the Edison during the Start-up phase. The Plant Performance Report will be distributed to all the project Participants and Parties. The distribution will be limited and controlled by Edison.

Monthly Progress Report – In addition to reports and documents generated to meet other requirements of the O&M Contractor's activities, a Monthly Progress Report will be provided by the O&M Contractor during the initial T&E Plan (first year of operations) period up to the initiation of Test 14, to provide timely information on plant status before the plant enters the power production phase. Such a report would complement the Test Reports prepared by the T&E team and describe the operating conditions at the time the tests are being conducted. The Monthly Progress Report should summarize plant conditions from an O&M viewpoint, including participation in the T&E Plan.

The following, minimum content is suggested:

1. Monthly plant availability as a function of time the plant was available for testing, whether or not tests were performed. Data reported would include, the equivalent day outage total, weather-related downtime, equipment failure-related downtime, and estimate of the number of days required to finish each test.
2. Test status tabulation, including test number, number of test variations conducted during the previous month, and current month, number of variations planned for next month, and number accumulated. The T&E Team and the O&M Contractor will cooperate in providing that data so that both groups are aware of the testing status and expectations.
3. Major component failures, causes, and maintenance status.
4. Major component and subsystem status, e.g., deferred repair/maintenance, current operating condition (up or down).
5. Critical depletion items in spare parts inventory.

When the plant enters the power production phase i.e., Test 15, the monthly Plant Performance Report should replace this report.

Operator's Daily Log

2.6 Operating and Maintenance Costs

The objectives for compiling cost data are as follows:

1. Acquire operation and maintenance (O&M) cost data and reduce it into cost summaries by system, major items of equipment, and trade groups.
2. Identify principal O&M cost drivers and attempt to reduce costs.
3. Predict O&M costs for Solar 100.

Operation and Maintenance Costs – The costs recorded by the O&M Contractor will include the cost of consumable materials and supplies, contract services, and replacement and spare parts. The O&M Contractor will also supply the man-hours and associated skill levels expended at Solar Two. The cost of station service energy will be determined and included. The T&E team will extrapolate the recorded information to estimate O&M manpower costs for the commercial plant. The T&E tests will identify the parasitic power required to operate the plant so that it can be modified as appropriate for potential applications at future plants.

The Maintenance Database records of hours required by each trade to perform their duties and the consumables used, will allow the T&E team to associate and tabulate the time requirements and costs for each maintenance activity.

2.7 Equipment Lifetime

The objectives of this evaluation are:

1. Estimate the cyclic damage to components due to thermal cycling.
2. Compare the actual thermal environment to the predicted environment and suggest design changes or changes to operation to alleviate stressful conditions.
3. Monitor the hot and cold tanks in an attempt to determine the stresses in the walls and wall-to-floor joint as a result of filling and emptying.
4. Continue to extend the database on heliostat mechanism and reflective surface degradation in a desert environment.

Heliostats – The heliostats used at Solar Two are not closely representative of heliostats that will be used in future solar central receiver plants. They are, however, similar enough to make it worth the effort to record environmental damage to painted structures, electronics enclosures, field wiring, and other items that will be the same in solar central receivers for the next 50 years.

Receiver – In a solar central receiver, the temperature cycling that a receiver endures largely defines its length of life. The Solar Two receiver is designed to endure 1,200 full strain range cycles of 10 °F per year at the receiver-tube-to-manifold joints. Ten thermocouples are placed on the tube-to-manifold joints of selected outlet headers. Ten thermocouples are placed on the tube-to-tube clip junctions on both east and west strings of panels. Twenty thermocouples are placed on each panel header. All 60 thermocouples will be recorded at a rate of 1 sample per second whenever the data acquisition system in operation.

The T&E Team will review the receiver thermocouple data to identify times when the receiver was thermally stressed beyond design (10 °F/second). Means for mitigating stressing conditions will be proposed. In addition, the Test and Evaluation Team will use the method of Jones and Stephens[a] to determine the effect of operation on the receiver life. If the receiver life seems to be consumed at an unanticipated rate, the overall design and operation of the receiver will be examined for changes which insure receiver lifetime will meet or exceed design predictions.

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a W. B. Jones and J. J. Stephens, Solar Receiver Design: Treatment of Creep-Fatigue Interaction," SAND93-0754, Sandia National Laboratories, January 1994

Steam Generator – The steam generator is similar to the receiver in that it experiences many start-up and shutdown cycles. It is different in that it does not respond to cloud transients, but variations in demand by the grid. For Solar Two, the variations in demand will be essentially non-existent because of the small output of Solar Two relative to the total capacity connected to the grid.

The steam generator will be monitored for leaks and other thermal cycling problems via the maintenance reports. A daily evaluation of temperature data for the steam generators is not planned. If problems develop with the steam generators, historical data can be recalled and scrutinized, and new instrumentation installed for determining the cause.

Hot Nitrate Salt Storage Tank – Thermocouples and capacitance strain gages will be installed on the walls of the hot nitrate salt storage tank. The instrumentation is placed at points in the tank where peak stresses are anticipated. The instrumentation would be brought to a local connector; one or more on each tank in accessible locations. A portable data logger will plug into this connector and record data during experiments. Data will not be taken continuously.

2.8 Environment and Safety

Little new work is anticipated regarding the environmental impact of Solar Two. The new areas of interest specific to the molten salt nature of Solar Two are:

1. Glint hazard associated with a receiver operating at a high flux level.
2. Handling and personnel hazards associated with molten salt in a working plant.
3. Corrosion limits.
4. Extent of salt contamination with metals leached from the plant piping.